CLASSIFICATION AND DENSIFICATION OF MUNICIPAL SOLID WASTE FOR BIOFUELS APPLICATIONS

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ABSTRACT

Municipal solid waste has been gaining interest as a potential feedstock for biofuels development as it is highly organic in nature and it is a waste product requiring very little processing to become a suitable feedstock. The main focus of this research project was to evaluate whether municipal solid waste (MSW) is a good source for bioenergy development, in particular, as a feedstock for conversion to biofuels. And if densification of MSW is a feasible process to integrate into waste disposal systems in Canada. These topics were addressed through a comprehensive review of classification of MSW in Canada with focus on suitability for biofuels development and a subset of experiments that produced information on the characteristics of MSW refuse-derived fuel (RDF) and the parameters required to produce a quality, densified fuel product.

A review of existing systems in Canada was conducted to establish how different regions currently classify waste; then, a classification framework produced specifically for energy recovery from MSW was used to analyze the strengths and gaps in those existing systems. Finally, a discussion regarding the suitability for biofuels development in each region was made based on the analysis. The City of Edmonton was used as the reference jurisdiction due to their established waste-to-biofuels project, and a geographic distribution of regions that were reviewed included Vancouver, Saskatoon, Toronto, and Halifax. The review determined that most jurisdiction classify MSW by material or product, with the former method being more suitable for investigating alternative utilization methods. Each region has potential for pursuing biofuels development, however, the greatest barrier appears to be whether there is a driving socio-political reason for doing so in the area.

Characterization of MSW-RDF fluff sample received from Edmonton showed that the composition of the material was approximately 35% paper, 22% plastics, 14% fabrics, 6% organics/wood, and 23% fines by mass. The RDF was densified, as well as the biodegradable (paper and wood) fraction of the RDF stream

to compare quality of pellets for the two material compositions. A characterization of the thermochemical and biochemical properties of MSW RDF-fluff was conducted to evaluate the suitability of MSW RDF-fluff for biofuels application. The ash content of RDF material was 19-39% while that of the biodegradable material samples was 20-23%. Proximate analysis resulted in a CHNS ratio of 33-41% carbon, 5-6% hydrogen, 0.6-0.8% nitrogen, and 0.2-0.5% sulfur for all samples. From the results of the proximate analysis, the higher heating value (HHV) for MSW RDF-fluff was calculated to be 14-16 MJ/kg. Fibre analysis of the biodegradable fraction determined that it contained 28% insoluble lignin, 1 % soluble lignin, 22% glucose, and 0% xylose.

A single pelleting trial was conducted to examine the compaction parameters that would produce high quality pellets: grind size, moisture content, pelleting pressure, and pelleting temperature. It was determined that quality pellets, for both materials, were formed at a grind size of 6.35 mm at 16% moisture under pelleting conditions of 90°C and 4000 N applied load. The compact density of pellets produced from RDF ranged from 880-1020 kg/m^3; the compact density of the biodegradable pellets ranged from 1120-1290 kg/m^3. Fitting of the Walker and Jones models to the experimental data both indicated that the biodegradable material fraction has a higher compressibility than the RDF material, where neither moisture content nor grind size at all levels had a significant effect on the compressibility of either material. The Kawakita-Lüdde model estimated the porosity of the pelleted samples, while the Cooper-Eaton model indicated that the primary mechanism of densification was particle rearrangement. Application of the Peleg and Moreyra model for analysis of relaxation properties of the compressed materials determined the asymptotic modulus of the residual stress to be between 89 and 117 MPa for all experimental parameters; however, the RDF material produced more rigid pellets than the biodegradable material.

Pilot-scale pelleting was then completed to emulate industrial pelleting process utilizing the parameters from the single pelleting operation that were deemed to produce quality pellets. All six of the sample treatments produced durable pellets (88-94%), with the ash content around 20% for all samples. A techno-economic feasibility study determined that 6.35 mm diameter pellets could be produced for an average cost of \$38/Mg and includes both size reduction and densification procedures, although the aggressive process of the size reduction required indicates that it may not be a technically feasible option.

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Forever grateful,

DEDICATION

This thesis is dedicated to my supportive father, Ralph Sprenger, P. Eng.

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NOMENCLATURE

Abbreviations	
ANOVA	Analysis of variance
ASABE	American Society of Agricultural and Biological Engineers
AAFC	Agriculture and Agri-Food Canada
ASTM	American Society for Testing and Materials
BFN	BioFuelNet
CD	Construction and Demolition
CHNS	Carbon, Hydrogen, Nitrogen, and Sulfur
CSBE	Canadian Society for Bioengineering
d.b.	Dry basis
EWMC	Edmonton Waste Management Centre
GHG	Greenhouse gas
HHV	Higher heating value
HHW	Household hazardous waste
HRM	Halifax Regional Municipality
ICI	Industrial, commercial, and institutional
MSW	Municipal solid waste
NREL	National Renewable Energy Laboratory
PAR	Percent average relaxation
RDF	Refuse derived fuel
SPU	Single pelleting unit
US EPA	US Environmental Protection Agency

w.b.	Wet basis
WtE	Waste to Energy

Symbols	
A_a	Cross-sectional area (m^2)
a_1	Kawakita-Lüdde model constant
a_2	Cooper-Eaton model constant
a_3	Cooper-Eaton model constant
b_1	Kawakita-Lüdde model constant
b	Walker model constant
b'	Jones model constant
C	volume ratio
d	Diameter of the tablet (mm)
E_a	Asymptotic modulus, (MPa)
F	Load at fracture (N)
F_e	Final relaxation force (kN)
F_0	Initial relaxation force (kN)
$F(t)$	Relaxation force at time t (kN)
k_1	Cooper-Eaton model constant
k_2	Cooper-Eaton model constant
k_3	Peleg-Moreyra model constant
k_4	Peleg-Moreyra model constant
l	Thickness of the tablet (mm)
m	Walker model constant
m'	Jones model constant
P	Pressure (MPa)

t	Time (s)
T	Temperature (K)
V	Volume of compacted material (m^3)
V_o	Initial volume at zero pressure (m^3)
V_s	Void-free solid volume (m^3)
V_0	Pellet volume immediately after pelleting (m^3)
V_{14}	Pellet volume after 14 days of relaxation (m^3)
ε	Strain
ρ	Compact density (kg/m^3)
σ_x	Tensile strength of (MPa)

Chapter 1

1 Introduction

1.1 Background

Municipal solid waste (MSW) consists of a waste disposed by a city's residents, and is comprised of primarily of food/yard waste, paper, plastics, and textiles. In Canada alone, nearly 25 million tonnes (Mg), or 777 kg/capita of MSW is disposed of annually (Statistics Canada 2014); of that, only a third is diverted through recycling, composting, or similar programs, the remainder is sent to landfill. With a land area over 9 million km^2, space for landfilling of MSW has never been a concern in Canada, unlike in other regions of the world. However, landfilling also accounts for 22% of the national methane production, which poses an environmental concern as methane is a greenhouse gas (GHG), 25 times more potent than CO_2 (Environmental and Climate Change Canada 2014). On another front, the world is very eager to look to alternatives for fossil fuels since they are a leading cause of climate change and air pollution; biofuels using a very broad range of biomass feedstocks and conversion methods are being researched for this purpose. Municipal solid waste has been gaining interest as a potential feedstock for biofuels development as it is highly organic in nature and it is a waste product requiring very little processing to become a suitable feedstock. With a higher heating value (HHV) of about 16 MJ/kg (Freidl et al 2005), there is around 267 PJ of energy stored in Canadian MSW annually destined for landfill. The availability and effectiveness of technology is not widely available, therefore limited industrial applications are currently operational.

1.1.1 Municipal Solid Waste Classification

Characterization studies are a method of gauging the baseline composition of a waste stream for a particular region; completed by sampling and sorting procedures. These studies are valuable for making decisions regarding waste management plans and for maintaining transparency to tax-payers. Classification on the other hand, refers to the means in which a waste stream is sorted; dependant on the processing intended for the waste stream. There are various processing technologies that are utilized or have potential in waste management operations, ranging from treatment and disposal to recovery and utilization; the applications used are dependent on the needs and goals of a particular jurisdiction. Table 1.1 summarizes the processing technologies for waste management and the purpose of each.

Table 1.1: Processing technologies for municipal solid waste.

Processing Technology	Purpose
Physical	
Sorting [a]	Material recovery
Recycling [abc]	Waste reduction/recovery
Size Reduction [c]	Waste treatment
Chemical	
Catalytic conversion/Partial Oxidation [d]	Carbon recycling
Pyrolysis (energy recovery) [b]	Waste utilization
Biological	
Composting [bc]	Waste utilization/recovery
Anaerobic Digestion (energy recovery) [abd]	Waste utilization
Ethanol Fermentation [b]	Waste utilization
Thermal	
Incineration [abc]	Waste disposal/ treatment
Combustion (energy recovery) [ab]	Waste utilization
Pyrolysis (energy recovery) [b]	Waste treatment/utilization
Gasification (energy recovery) [b]	Waste utilization
Landfill	
Landfilling [abc]	Waste disposal
Landfill gas recovery [a]	Gas recovery

[a] (Demirbas et al. 2011), [b] (Adapa et al. 2006), [c] (US EPA 2013b), [d] (Naik et al. 2010)

Relative to the rest of the world, very few characterization or classification studies have been conducted in Canadian jurisdictions; there are several reasons that can account for this. First, these studies are often completed when a demand for changes to current waste management plans is forefront, particularly in the case of landfilling. With the abundance of land area per capita, Canada is not forced to find alternatives apart from improving an environmentally conscious image and extending innovation. Further, typical characterization studies are resource intensive; requiring significant time, labour and monetary commitments. Therefore, unless a project has been proposed to introduce a progressive technology to an area, few studies have been completed. This section reviews the status of both the characterization and classification approaches to MSW management across Canada to date.

1.1.1.1 Characterization Studies

Also referred to as waste composition studies, the purpose of a characterization study is to establish a baseline reference of the relative amounts of each material present in the waste stream.

Many jurisdictions use a variation of the ASTM International standard D5231-92 (ASTM 2008) to guide the methodology for sampling, sorting, and analyzing of their MSW streams. It is used more for the sampling protocol, which suggests the appropriate sample size and number of samples to gather in order to acquire a proper representation of the population. The minimum suggested number of categories for sorting is thirteen (Table 1.2), with the option for individual jurisdictions to adapt and refine the list to meet the purposes of their intended study. A review of characterization studies throughout the world provide material lists with anywhere from 10 (Sethi et al. 2012) to 126 subcategories (Oregon Department of Environmental Quality 2009).

Table 1.2: Minimum recommended component categories for sorting municipal solid waste (ASTM 2008).

	Categories	
Mixed Paper	Plastic	Ferrous
High-grade paper	Yard waste	Aluminum
Newprint	Food waste	Glass
Corrugated cardboard	Wood	Other inorganics
	Oher organics	

A predominant number of characterization studies are completed to gather an in-depth look at what is in the MSW stream and where it is coming from (demographic sampling analysis); allowing speculation as to where waste management plans require attention. Saskatoon recently completed a detailed composition study prior to implementing a curbside recycling program in the city; they will complete another study in the near future to compare the changes in composition and determine the success of the program (HDR Corporation 2013).

Composition studies also guide the organization of MSW classification methodologies. Once an appropriate classification structure has been developed, the characterization can assist with determining the feasibility of particular processing technologies based on the relative waste composition. For example, gasification waste-to-energy processes can utilize non-putrescible organic matter; however, higher content of inert materials present will reduce the efficiency of the process.

1.1.1.2 Waste-to-Energy Classification

An extension of waste characterization, classification of municipal solid waste aims to logically sort the material composition in a means that is beneficial for determining feasibility of potential waste processing technologies. The emphasis of this classification is towards waste-to-energy (WtE) opportunities. The primary waste-to-energy technologies consists of: combustion, gasification, pyrolysis, and anaerobic digestion.

All of these involve the recovery of organic carbon in the feedstock and its conversion into a usable form of energy. A review of published literature suggests a common method of classifying MSW for WtE applications based on the understanding of the processes involved and operating conditions required. There are very few classifications of MSW in particular for biofuels applications, however they all appear to agree on four significant categories based on the physiochemical characteristics of the materials and the potential WtE applications for each fraction Table 1.2.

Table 1.3: Literature on municipal solid waste classification methodologies.

Processing Potential	Classification Methodology			Example Materials
	Adapa et al. (2006)	Tatarniuk (2007)	EWMC (2015)	
Recycling Landfill	Inorganic/ Non-combustible	Inert fraction	Inert fraction Inorganics Bulky Materials	Metals Glass/Ceramics Rocks/Soil
Composting Anaerobic digestion Ethanol fermentation	Organic/Combustible Putrescible Cellulosic	Wet putrescible	Compostable organics	Food waste Grass clippings
Combustion Pyrolysis Gasification	Organic/Combustible Non-putrescible Cellulosic	Dry combustible	RDF (Woody wastes, paper, plastics, textiles)	Wood waste Paper/Cardboard Natural Textiles
Combustion Pyrolysis Gasification	Organic/Combustible Non-putrescible Non-cellulosic	Plastic		Synthetic textiles Plastics Rubber

As such, an effective classification system for biofuels does not require a characterization study that consists of a vast subcategory list; although these lists can be sorted into functional groups based on their potential utilization or energy contribution.

A review of waste management and conversion processes suggested a general waste classification outline that focuses more on the origination of the waste, rather than the characterization of the waste components based on their thermochemical attributes. This included types such as residential waste, supermarket waste, and medical waste (Demirbas 2011). This method works more effectively as a characterization approach rather than a classification for biofuels applications.

There are other publications on waste classification methods that are focused on waste management indices such as physical and decomposition attributes for transportation, storage, and landfill disposal and maintenance; however, they are irrelevant to the purpose of this classification for waste-to-energy applications. However, if the eventual goal is to create an overarching standard for municipal waste classification that can be adapted for any particular use, these documents would be valuable to consult.

Due to the fact that waste-to-energy technologies are still in early development, in particular with the focus on advanced biofuels, there has been little focus on classification for thermochemical operations. It would be valuable to establish an effective classification to assist in determining whether additional processing and separation to usable fractions of the MSW stream would be valuable for these applications.

1.1.1.3 International Characterization Approaches

Little attempt has been made to classify MSW in other countries around the world; however, there have been alternate attempts to characterize the waste generated. This is due to a greater emphasis on waste management protocols that deal with disposal alternatives from landfill as the land area is diminished and in regions where there is a significantly greater population density compared to Canada.

The ASTM International standards organization has a methodology for completing municipal solid waste composition studies. It is utilized to some extent by many jurisdictions, and allows for customization of the sample size and sorting categories to suit the needs of the study group. It recommends a minimum of thirteen categories (ASTM Int'l 2008) (Table 1.2).

Many US statewide studies utilize a material flow approach to quantify the waste composition. This is completed by combining the overall material waste stream quantity with production data of materials that enter the waste stream (Dahlén and Lagerkvist 2008). There does require an adjustment to consider the lifecycle of many materials however (US EPA 2006).

A common consideration in several studies is the effect of seasonality on the waste stream and the means by which this could impact the composition of the MSW; higher moisture contents due to higher organic matter during the growing season can reduce conversion efficiencies. Quantity of waste does not seem to be effected by time of year.

Most of the variations in approaches to characterization studies around the world focus on demographic relationships in the way that they collect and compare fractions of the municipal waste stream (Dahlén and Lagerkvist, 2008). This outlook is important for waste management plans, but is not of added benefit to characterization for waste-to-energy applications.

1.1.2 MSW as a Biofuels Feedstock

Municipal solid waste is considered a feedstock for the production of advanced biofuels based on its ability to contribute to the global energy demand while being a more sustainable feedstock and means of waste disposal (BioFuelNet 2015).

1.1.2.1 Composition

As previously mentioned, MSW consists of disposed paper, plastic, food scraps, textiles, glass, metals, etc. The components of this waste stream that can be utilized for conversion into energy are organic (carbon-based), including plastics, paper, lignocellulosic materials (wood, leaves, food scraps), textiles, and rubber.

Not all technologies require additional sorting of the waste stream, however the efficiency of the process can be increased if this is done. Inert materials, such as metals, glass, and soils can be removed from the waste stream using magnets and sieves (City of Edmonton 2011). For thermochemical conversion technologies such as gasification, the inert materials are unable to contribute to the energy potential and only reduce the overall energy density of the sample. MSW that has been sorted is often then shredded to create a more uniform feedstock called refuse derived fuel (RDF-3) (ASTM Int'l 1998). This RDF is the material that is submitted to the waste-to-energy technology facilities.

A withdrawn ASTM International standard outlining the terminology surrounding RDF categorized them based on the level of processing that occurred prior to being used as a final feedstock (Table 1.3); the standard was withdrawn due to limited use by industry, an analogous standard exists for coal (ASTM Int'l 2004). These classifications can be helpful for comparing the level of processing required for different WtE systems.

Table 1.4: Refuse-derived fuel classification (ASTM Int'l 2004).

Classification	Description
RDF-1	Wastes used in discarded form.
RDF-2	Wastes processed to coarse particle size with or without ferrous metal separation.
RDF-3	Processed to remove metal, glass, and other inorganic materials. Particle size such that 95 weight % passes through a 2-in. square mesh screen.
RDF-4	Combustible waste processed into powder form, 95 weight % passing 10-mesh screening.
RDF-5	Combustible waste densified (compressed) into the form of pellets, slugs, cubettes, or briquettes.
RDF-6	Combustible waste processed into the liquid fuels.
RDF-7	Combustible waste processed into gaseous fuel.

1.1.2.2 Waste-to-Energy Projects

There are only a few operational municipal pilot or full-scale waste-to-energy projects currently in operation in Canada. There are however, several jurisdictions that have initiated initial planning and design for WtE investments. Enerkem is the only company in collaboration with a municipality that produces advanced biofuels, however the majority of WtE projects only output electrical power; both may use thermochemical conversions however, which can benefit from the development of RDF feedstocks.

Edmonton Waste Management Centre (EWMC) has collaborated with Enerkem to develop the world's first industrial waste-to-biofuels and chemicals facility. This plant utilizes Enerkem's gasification technology to create advanced biofuels such as methanol and ethanol, with the intention to be able to produce various chemicals from the process. It is able to convert approximately 100,000 tonnes of RDF waste to 38 million litres of fuel and chemicals (City of Edmonton et al. 2011). The process uses a RDF-fluff which would be classed as an RDF-3 feedstock (Table 1.3). EWMC is the primary collaborative partner with the University of Saskatchewan under the BioFuelNet project studying the processing of MSW feedstocks. Their greatest inquiry is whether densification (briquettes or pellets) of the RDF-fluff that they are currently using as a feedstock would improve the overall energy conversion rate. Further research and development from this facility may indicate potential for future MSW advanced biofuels production applications in Canada and the world.

Halifax Regional Municipality has partnered with Fourth State Energy to create Nova Waste Solutions Inc. with the intent to develop a Waste-to-Energy facility. They have contracted a detailed engineering study to develop a design, feasibility, and environmental assessment (Fourth State Energy 2014). The facility would utilize a plasma gasification technology to convert 131,000 tonnes of waste to 50 GWh of electricity annually (Nova Waste Solutions Inc. 2013). The technology is able to utilize a wide range of waste biomass in various states; including raw MSW, RDF-fluff, agricultural residues, and wood waste (CHO Power 2011).

Several jurisdictions have collaborated with innovative corporations to develop mass burn/combustion facilities to divert MSW from landfills and utilize energy from the organic matter present. The Durham-York and Metro Vancouver's WtE facilities are large-scale examples of these operations (Peel Energy Recovery Centre 2015). The regions of Hamilton, ON, Guelph, ON, Ottawa, ON, and Wesleyville/Port Hope, ON have begun investigations into WtE projects; this displays the proactive outlook of particular regions to develop sustainable energy solutions.

1.1.3 Biomass Densification

Compaction of low bulk density biomass is a desirable operation for producing a quality feedstock for various feed and energy industries. Biomass is difficult to handle, transport, store, and utilize in its natural form due to the fact that it is typically high in moisture, irregularly shaped, does not flow well, and has a low bulk and energy density (Adapa et al. 2013). Densification into pellets or briquettes can increase the bulk density of a raw product from 40 - 200 kg/m^3 to a compact density of 600 - 1200 kg/m^3 (Mani et al. 2003). Providing a more uniform shape and density to the raw product allows the utilization of handling and storage systems designed for grains. A more uniform feedstock is also desired for efficient conversion to biofuels and bioproducts by biochemical or thermochemical means (Naik et al. 2010). However, densification does add another cost to the economic and energy requirements for producing the feedstock and the process conditions required to produce quality pellets or briquettes is also unique to each type of raw biomass (Adapa et al. 2013).

1.1.3.1 Methods

The main methods of densifying biomass for biofuels applications are through the use of a pellet mill or a briquette press. Pellets that are produced using a pellet mill are cylindrical in shape measuring approximately 6 mm in diameter and 15 mm in length depending on the application and the equipment (Tumuluru et al. 2011). The advantage of pelleting biomass is that it creates a product that is dense, free-flowing, and uniform. Densification increases the volumetric energy content (calorific value) of the sample which is significant for the efficiency of any biofuels application (Demirbas and Sahin-Demirbas 2009). Pelletization permits densities greater than 1100 kg/m^3 which is more than 10 times the original density depending on the original state and identity of the material; this translates to a proportional increase in the energy density of the product as well (Tumuluru et al. 2011). Therefore, it can be implied that densification of bio-products would improve the conversion efficiency of a generic biofuels operation; there is no literature indicating whether there is a density too high for conversion, after which efficiency decreases again. Improved uniformity (size, shape, density) also allows more consistent operating conditions for whichever waste-to-energy application is being utilized. A limitation of pelletization is that to prepare the material for densification, it must first be ground to a smaller particle size to ensure that the material is able to bind sufficiently; this size reduction process, along with pelleting are energy and cost intensive.

Another method that is utilized for densification of biomass samples is briquetting; it can produce cylindrical briquettes that are approximately 40 mm in diameter and in length (Tumuluru et al. 2011). The advantages of briquetting are the same as pelleting in terms of creating a product that is denser, in terms of mass and energy, and more uniform, just in a larger product. Density is typically lower than hat of pellets. An additional advantage of briquetting is that the process can handle larger particle sizes of the raw material and higher moisture contents (Tumuluru et al. 2011). These are advantageous if there is concern regarding the ability to process the material sufficiently prior to densification.

1.1.3.2 Pretreatment of Biomass

There are two purposes for the pretreatment of biomass prior to densification. The primary reason is to counteract the resistance of lignocellulosic biomass to degradation; a significant limitation for natural binding during pelletization, as well as for particular thermochemical and biological processes (Iroba and Tabil, 2013). Another reason for pretreatment is to improve the quality of the pellets in terms of properties relevant to waste-to-energy conversion (Tumuluru et al. 2011).

There are numerous pretreatment methods that have been studied extensively; however, the effectiveness of each depends on the feedstock, in particular, the proportion of cellulose, hemicellulose, and lignin. Lignocellulosic fractions of MSW would consist of the paper products, food waste, wood materials, and natural fibre textiles (e.g. cotton). The cellulose fraction consists of a crystalline matrix with some amorphous segments; this crystalline structure is one of the major hindrances for hydrolysis of the sample (Iroba and Tabil 2013). Hemicellulose has an amorphous structure which links the cellulose and lignin crystalline molecules within the plant material. Lignin is the main cause of resistance to degradation as it is a complex, cross-linked macromolecule (Iroba and Tabil 2013); it is the target source for pretreatment required due to limited natural binding characteristics.

The alternative reason for pretreatment of biomass feedstock is to improve the overall thermal and mechanical properties of the sample; there is a trade-off between the added cost of energy inputs and the benefits from increased quality. Certain treatments can improve the calorific value, pellet durability, moisture content, and product uniformity (Tumuluru et al. 2011). This is one of the primary reasons for investigating the effects of pretreatment on MSW and RDF as the presence of plastics in the waste stream provide significant binding attributes already, and the material does not rely on the degradation of lignocellulosic fractions to contribute to the pellet quality.

There are several different pretreatment technologies that can be applied to biomass feedstocks and like WtE conversion technologies, they are classified as either physical, biological, or chemical treatments.

Grinding and particle size reduction of biomass samples is a physical pretreatment process which provides some assistance to lignin breakdown. The main purpose of grinding however, is to increase the surface area of the particles which allows potential for greater binding attributes. Smaller particles also contribute to improved durability of pellets (Tumuluru et al. 2011).

Another physical pretreatment method is the pre-heating and/or steam explosion of the sample. These applications render the lignin binding characteristics to be more available during densification (Iroba and Tabil 2013). This reduces the overall energy requirement for producing the pellets.

Torrefaction of biomass refers to thermal pretreatment under inert atmosphere conditions (Chen et al. 2015). Induced decomposition reactions remove most of the volatile components in the sample as well as rendering the lignin components more available to binding (Tumuluru et al. 2011). The benefits of torrefaction can result in improved energy density, lower moisture content, improved reactivity, and more uniform properties; all of which are advantageous to thermochemical WtE applications.

Ammonia fibre explosion (AFEX) is a thermochemical pretreatment that utilizes aqueous ammonia to degrade the lignocellulosic fractions of a biomass sample (Iroba and Tabil 2013).

Microbial pretreatment of lignocellulosic biomass can utilize fungal or bacterial microorganisms. The main focus is to degrade the lignin component of the material that is resistant to enzymatic hydrolysis. It provides a low energy option that reduces the need for severe thermal treatments. Bacterial options involve the exploitation of species that are naturally occurring in the gut of ruminant animals and are used to start breaking down lignocellulosic plant residues (Canam et al. 2013). A more common microorganism to utilize is rot fungi (brown and white varieties) as they are able to degrade the lignin fraction further than bacterial species (Canam et al. 2013). Each biological pretreatment method provides a low temperature, environmentally friendly (no harmful chemicals) alternative to prepare lignocellulosic biomass for densification.

1.1.3.3 Feedstock Variables that Influence Biomass Densification

Biomass feedstocks are diverse in their physical characteristics; moisture content, particle geometry, and biochemical composition each influence the results of densification, such that pretreatment and or conditioning of the raw biomass may be required to produce higher quality pellets.

Moisture in a biomass sample is both beneficial and detrimental for densification processes, therefore, a moisture content range that produces quality pellets is restricted. Water present in a sample increases the contact area of particles, resulting in increased bonding via van der Waal's forces (Mani et al. 2006). At higher moisture contents (>25%) however, the incompressible nature of water likely prevents the complete deformation of the particles (Pickard et al. 1961). Hence, as moisture content of biomass is increased, the pellet density subsequently decreases (Mani et al. 2006). Further, clogging of the pellet die is known to occur at moisture contents of 16-18% for feed materials. In general, moisture contents between 8 and 12% are typically optimal for most cellulosic biomass feedstocks (Sokhansanj et al. 2005).

Particle size distribution in addition to geometric mean diameter have an effect on the quality and density of pellets (Payne 1978). Finer particles have greater surface area available for binding; this results in higher durability pellets, but also a greater absorption of water molecules (Tumuluru 2011). Larger particles create natural fissures in the compacted product that can become points at which breakage occurs (Mani et al. 2003). Fine grinding of biomass is undesirable due to the higher production cost; thus, a distribution of different particle sizes would optimize pellet quality. Further, a mixture of different particle sizes increases the efficiency of particle rearrangement such that there are nearly no inter-particle spaces present (Kaliyan and Morey 2009).

The biochemical composition of a feedstock (i.e. the fraction of starch, cellulose, protein, etc.) will also affect the densification process and may indicate the necessity for pretreatment such as is the case of lignocellulosic materials which are very resistant to deformation (Tumuluru 2011). Further, plastics and composite materials present in waste streams may interact with other process variables; for example, most plastics are hydrophobic, therefore, they will resist inter-particle bonding at higher moisture contents.

1.1.3.4 Process Conditions that Affect Biomass Densification

Regardless of the densification process, there are certain process conditions that can affect the quality of pellets and/or briquettes; these include temperature, pressure, retention time, and die geometry. An appropriate balance of these conditions will also optimize the energy requirement relative to the desired level of quality (Adapa et al. 2013).

Heat can be introduced into the densification process by means of heating the pelleting die or by preheating the feedstock material. Frictional heat is also generated during the densification process in a continuous pellet mill operation (Mani et al. 2003). Higher temperatures reduce the force required to achieve a desired compact density (Hall and Hall 1968); thus, the process requires less load for a desired compaction level, reducing the power consumption. Increasing the temperature of the process also increases the upper limit of feedstock moisture contents that can produce quality pellets (Tumurulu et al. 2011). Process temperatures greater than 90°C are desirable for lignocellulosic biomass as this value corresponds to the glass transition temperature of lignin, which in its native state is resistant to compaction; however, lignin acts as a binder when its structure is disrupted, such as during the glass transition phase (Kaliyan and Morey 2006).

Pressure is a critical factor in terms of the level of compaction that can be achieved and the binding mechanisms which are involved. As the compressive load increases, the compact density approaches the particle density for that sample (Mani et al. 2003). Under high pressures, natural binding components, such as starches, proteins, and lignin may be squeezed out of their respective particles, contributing to inter-particle bonding (Thomas et al. 1997). However, there is an optimum pressure at which the mechanical strength of the material due to plastic deformation is reached, beyond which little increase in density is observed relative to the energy required for production (Yaman et al. 2000).

The length of time during which the biomass is held within the pellet die under applied load is required to reduce the effect of ‘spring-back’ which occurs due to elastic deformation during compression. Since optimum pressures seek to achieve complete plastic deformation, it is understandable that the hold time has a greater effect on compaction at lower pressures; such as was observed by Li and Liu (2000) for the densification of sawdust. Ultimately, the time at which the material is held under compression loading relates to the relaxation characteristics of the feedstock, and therefore it can affect the relaxed unit density of the pellet or briquette (Shaw 2008).

The die geometry and speed at which the pellet is extruded through the die has an impact on both pelleting and briquetting as they indicates the required pressure required to compact the material and overcome the friction of the inner die surface. The size of the die diameter also influences the rate of biomass that can be pelleted; smaller diameters restrict the flow of material and therefore increase the required power input. For a constant mass of material, dies with larger length to diameter ratios produce pellets with higher durability and density (Tabil and Sokhansanj 1996). Similarly, Kaliyan and Morey (2009) found that smaller pellet dies (approximately 6.1 mm) generally result in pellets with greater durability; however, such smaller dies typically plug when the material has a moisture content greater than 10% w.b.

1.1.3.5 Additives

It has become common practice for some applications to include certain additives to the material before densification to improve certain characteristics of the final product.

Binders have been utilized in the densification of biomass feedstocks to improve the durability of the final product where the natural binding characteristics of the particular feedstock are inadequate, even with the application of pretreatment. Some common binders include crude glycerol and colloidal clays (Lu et al. 2014).

A prior study was completed to investigate the effects of adding a fuel additive to a biomass sample for densification. This particular fuel additive, AK2, was stated to reduce the ash fusion during combustion and/or the slag and clinker formation during thermochemical conversion (Emami et al. 2013). Both are methods that can be used for waste-to-energy operations. This study also indicated that there is no detrimental effect to the durability, density, or specific energy of the compressed product.

1.1.4 Knowledge Gap

MSW is very heterogeneous and variable in nature, therefore it is important to fully understand how it is currently managed and the properties of the material in order to effectively move forward into utilizing it as a biofuels feedstock. Establishing a sense of how regions classify their waste would assist in determining a system that can be used as a framework to make decisions regarding the processing and utilization of MSW, particularly for biofuels development in jurisdictions across Canada. In order to improve the quality of MSW as a biofuels feedstock due to not being very uniform, hard to handle, and having a low bulk/energy density, densification is a desired process. Thus, establishing a knowledge of the physical characteristics of the raw MSW, the parameters that are required to produce quality pellets, and the physical and thermochemical properties of those pellets, is needed in order to efficiently and effectively produce a high quality feedstock.

1.2 Research Objectives

The main objectives of this MSc project were: (i) to review the classification of MSW for biofuels applications; and (ii) to assess the pelleting and physico-chemical characteristics of MSW-RDF fluff.

Specifically, the review of classification of MSW in Canada aimed to:

1. Compare the classification methods implemented in multiple Canadian jurisdictions and assess the potential for bioenergy opportunities in each;
2. Identify potential strengths and weaknesses in current classification systems; and from this, propose a standardized classification system to implement if current systems aren't sufficient; and
3. Analyze the waste stream composition and physical properties for the City of Edmonton.

The specific objectives of the densification study were to:

1. Determine the requirements for pre-processing of municipal solid waste, including sorting and size reduction;
2. Evaluate the compaction parameters and characteristics of pelleting MSW RDF-fluff to produce a high quality feedstock;
3. Emulate industry-scale pelleting of MSW RDF-fluff in a pilot-scale demonstration;
4. Determine the thermochemical and biochemical characteristics of MSW RDF-fluff pellets; and
5. Assess the techno-economic feasibility of scaling-up the pelletization of MSW-RDF fluff.

1.3 Organization of the Thesis

This thesis is organized and formatted according to the guidelines for manuscript-style theses of the College of Graduate Studies and Research at the University of Saskatchewan. It has six chapters, three of which are research manuscripts. The manuscripts presented in chapters 3 and 4 have been published in part in peer-reviewed journals or for presentation at a CSBE conference. The manuscript in chapter 2 has yet to be reviewed for possible publication. Within each of these three manuscripts, a transition section on the "Contribution of the MSc Candidate" is incorporated. The remaining three chapters include this introductory chapter, a chapter discussing the overlapping theme of this study (Chapter 5), and a final chapter consisting of conclusions and recommendations for future research (Chapter 6). A list of references is provided after Chapter 6.

The Appendix contains supplementary data for each of the three manuscript chapters.

1.4 Manuscript Content of the Thesis

Each of the manuscripts focuses on municipal solid waste as a feedstock for biofuels production. Chapter 2 reviews MSW classification systems in Canada and analyzes the suitability of those existing systems for pursuing biofuels applications. Chapter 3 evaluates the physical, biochemical, and thermochemical characteristics of MSW RDF as well as the compression and relaxation properties of this material. Chapter 4 focuses on pelleting of MSW RDF-fluff to produce a higher quality biofuels feedstock; the experiments consisted of single-unit pelleting, pilot-scale pelleting, and a concluding scale-up feasibility study.

Chapter 2

2 Review of Municipal Solid Waste Classification Systems in Canada to Analyze Potential for Biofuels Production

Contribution of the MSc Candidate

The MSc candidate conducted literature review, analyzed the outcomes, and prepared the manuscript on municipal solid waste classification in Canada. Her research supervisor, Lope G. Tabil, provided guidance during planning of the review methodology and editorial advice during manuscript preparation. External committee member, Phani Adapa, provided guidance for structuring the review and provided previously conducted research on this subject matter.

2.1 Abstract

Municipal solid waste (MSW) is being established as an advanced biofuels feedstock for thermochemical conversion. Edmonton has developed the first waste-to-biofuels collaboration with Enerkem Alberta Biofuels; however, Canada as an entire country is only recently entering the discussion on increasing landfill diversion rates by incorporating new technologies and programs, due to the fact that there is abundant land area available and have been few incentives to help make these new technologies as cost effective as landfilling. A comprehensive classification framework is required in order to effectively investigate the opportunities available for energy recovery from MSW. To support this aspect, first, a review of existing systems in Canada was conducted to establish how different regions currently classify waste; then, a classification framework produced specifically for energy recovery from MSW was used to analyze the strengths and gaps in those existing systems. Finally, a discussion regarding the suitability for biofuels development in each region was made based on the analysis. The City of Edmonton was used as

the reference jurisdiction due to the established waste-to-biofuels project, and a geographic distribution of regions that were reviewed included Vancouver, Saskatoon, Toronto, and Halifax. The review determined that most jurisdictions classify MSW either by material or product, with the former method being more suitable for investigating alternative utilization methods. Each region has potential for pursuing biofuels development, and while economic factors may play a role in what technologies are implemented, the greatest barrier appears to be the socio-political drive.

2.2 Introduction

Municipal solid waste (MSW) includes combustible and non-combustible household, commercial and industrial wastes that are usually deposited in municipal landfill sites. Combustible MSW is generally classified as a renewable fuel since up to 80% of the carbon content of MSW is biomass derived and therefore is renewable. The principal environmental concerns of MSW relate to the potential impact from inadequate waste management practices on human health and the environment, including soil and water contamination, air quality, land use and landscape. Recent studies show that the present systems of landfill and incineration (mass burn or combustion) disposal of MSW are not sustainable options as they cause significant environmental problems by emission of greenhouse gases (Jenkins, 2006; IEA, 2003, UK Environment, 2000).

Landfilling remains the major means of disposal of MSW in many cities in North America. Although sanitary or improved landfills, which minimize contaminations by leachates, are being commissioned in some cities, the problem of greenhouse gas emissions such as methane (CH_4) and hydrogen sulphide (H_2S) from landfills still remain to be alleviated. Methane has over 20 times more greenhouse gas effect than carbon dioxide (Biffa, 2005). The biological process-based technologies with relatively low reaction rates include composting, anaerobic digestion and ethanol fermentation, etc. The organic components of the MSW stream are typically utilized as compost or fuel for the marketable end product from biological processes (Gartner Lee, 2004).

The municipal solid waste is highly non-homogeneous since it consists of residues of nearly all materials used by humanity. The content of municipal solid waste varies with location, lifestyle, season, trends in packaging, local recycling schemes and local authority collection policy. Physical processing technologies are primarily designed to separate mixed MSW stream into combustible and non-combustible components. The process may also involve additional pretreatment of a segregated materials stream to make it more suitable for a designated utilization. Two major types of physical processes are recycling or materials recovery facilities and production of refuse derived fuel (RDF) composed of different MSW combustible components. The composition of MSW is influenced by the choice of waste management system. The complex composition of MSW coupled with the increasing awareness of the environmental hazards of waste disposal and lack of landfill sites have in recent years promoted the search by several municipalities for alternative waste treatment systems, including thermal conversion systems (IEA, 2001).

MSW consists of both organic and inorganic fractions that are disposed of by all sources within a municipality (Mor et al. 2006). This may include paper, plastic, glass, metal, food waste, wood, and other composite materials. It does not typically include construction and demolition (C&D) waste or waste water treatment sludge (Adapa et al. 2006).

Currently most MSW streams are collected by a jurisdiction and disposed of at sanitary landfill operations. Some regions utilize waste recovery facilities to collected recyclable or compostable materials from the waste stream. Other municipalities have resorted to incineration facilities to reduce the amount of waste being sent to landfill. The world has seen a growing need to search for waste management alternatives as the land area available for landfilling has diminished and concern over the state of the environment has heightened. European countries and other densely populated regions around the world have been at the forefront of developing these strategies as they are forced by limited space. Canada however, is only starting to investigate options, more from an environmental sustainability platform as landfill capacity is abundant and low-cost in most regions. In order for jurisdictions to evaluate potential thermo-chemical technologies for waste disposal alternatives, they must first analyze the way in which they currently classify their waste streams, as to what technologies are available to them in the future. A framework for assessing a city's energy potential from waste streams would be a useful tool for providing guidance for new transitions to updated waste management platforms in Canada.

Dixon and Langer (2006) compiled a list of existing MSW classification systems (Table 2.1), most of which are based on material type or physical properties.

Table 2.1: Existing systems for municipal solid waste classification.

Basis for differentiation	Parameters used for differentiation	Authors
Waste type	Density, shear parameters, liquid/plastic limit, permeability	Turczynski (1998)
Material groups	Part of composition	Seigel et al. (1990)
Organic, organic materials	Degradability (easily, slowly, non) Shape (hollow, platy, elongated, bulky)	Landva and Clark (1990)
Degradable, inert, deformable materials	Strength, deformability, degradability	Grisolia et al. (1995)
Material groups	Size, dimension	Kolsch (1996)
Soil-like (3-D structure), other	Index properties	Manassero et al. (1997)
Soil-like (3-D structure), non-soil-like (2-D structure)	Material groups	Thomas et al. (1999)
Mechanical properties	Material properties, weight, size, shape, organic, inorganic, soil-like, non-soil-like	Dixon and Langer (2006)
Material type, product type	Part of MSW composition	US EPA (2013a)
Thermochemical characteristics	Proximate and ultimate analysis	Zhou et al. (2015)

[a] Literature reported by Dixon and Langer (2006)

The most predominantly used classification system is a material-based characterization, standardized by the US EPA (Franklin Associates, Ltd. 1998). This scheme tabulates the relative fractions of each material found in a MSW sample which can be extrapolated for an entire population. The list of materials can be adapted depending on the needs of the jurisdiction completing the characterization. The results of a characterization study can be used to analyze the opportunities for physical, biological and chemical, energy recovery, or landfilling processing.

The diverse composition of material types in a MSW stream can be further differentiated by whether or not a material is organic, putrescible, or cellulosic; these physicochemical properties indicate whether energy can be recovered from a material, and if so, how that may be achieved. From this, Adapa et al. (2006)

developed a classification framework for energy recovery from MSW (Fig 2.1), incorporating different classification approaches to provide a system for identifying suitable means of producing energy based on the material composition of the waste. This template can then be applied to the results of a characterization study to determine the most suitable method of energy recovery for a particular jurisdiction.

MSW has been increasingly studied as a potential feedstock for biofuels applications in Canada and around the world; this opens an opportunity for greener energy options as well as a means of sustainably managing waste that has traditionally been sent to landfills. Therefore, the objective of this study is to review the current waste classification methodologies of five Canadian jurisdictions and apply the framework proposed by Adapa et al. (2006) to identify the potential for pursuing biofuels production in each case.

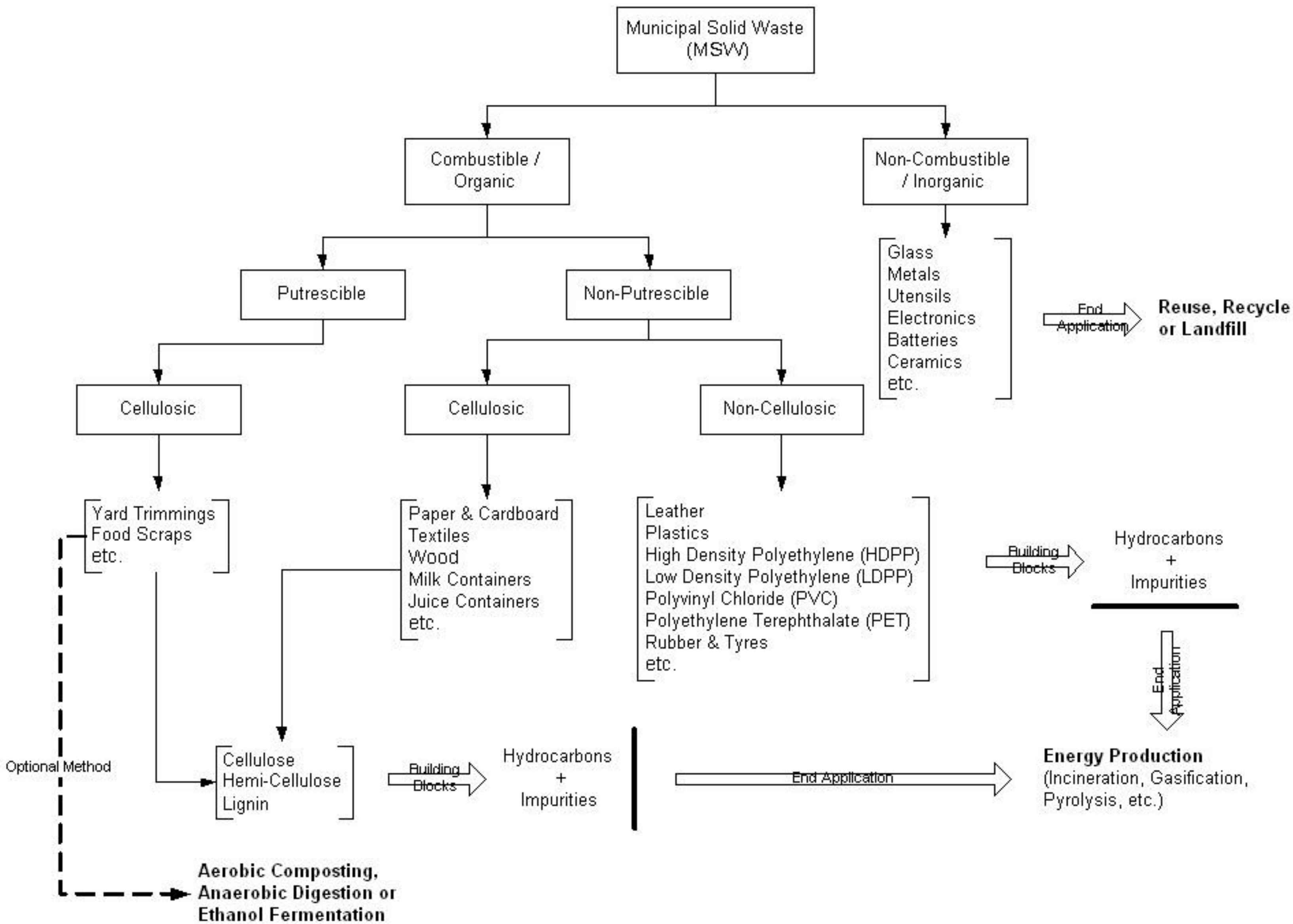

Figure 2.1: Municipal solid waste classification system for energy recovery (Adapa et al. 2006).

2.3 Methodology

The waste management operations of five Canadian jurisdictions were reviewed to determine their suitability for approaching the production of biofuels as a means of energy recovery from MSW. The elements of each waste management program that were considered were waste collection, current disposal processes, characterization study results, and sociopolitical goals for increasing landfill diversion rates and/or reducing environmental impact. The economic structure of each waste management program was not addressed, however, the cost of implementing alternative waste processing technologies would be a key factor when pursuing any new system.

2.3.1 Jurisdictions

A total of five Canadian jurisdictions – Edmonton, Saskatoon, Vancouver, Toronto, and Halifax – were chosen for this review to represent a thorough geographic and demographic comparison of waste conversion potential in Canada. The City of Edmonton is the only location in North America which boasts an operational biofuels production facility utilizing MSW as a feedstock. Saskatoon is the local jurisdiction interested in investigating a waste-to-biofuels operation, while Vancouver, Toronto, and Halifax round out the study with representation from western, central, and eastern Canada, respectively. A general background discussion on each municipality, including population and climate, will be provided as context for the subsequent review and analysis.

2.3.2 Review Methodology

Each jurisdiction's waste management division were reviewed in terms of their most recent characterization study and their current collection and disposal methods. The specificity of the material characterization study provides indication as to how a municipality classifies their waste. Highly categorized studies may indicate that the waste management division classifies their waste by product type (i.e. newspaper, HDPE, glass bottles, etc…), likely with the intentions of understanding the disposal habits of their population.

Broad characterization by material type (i.e. paper, plastic, metal, etc…) signifies classification in terms of utilization potential. Examination of the region's current collection and disposal methods indicates whether source separation is utilized or if the MSW is single-stream; it also specifies the existing infrastructure and waste processing methods. Results of the research into these physical operations will be cross-referenced with the waste management and environmental goals of the jurisdiction in question, from which a critical assessment of how MSW is classified in each Canadian region will be discussed. Specific emphasis will be made on whether attention was paid to the utilization potential on the MSW.

Upon review of the existing waste classification methodologies for each municipality, each case was examined in terms of the potential for biofuels production. The characterization study results and collection methods were subjected to the proposed energy recovery classification framework constructed by Adapa et al. (Figure 2.1). The framework identifies the processing technologies that could be implemented by each jurisdiction. The City of Edmonton will be examined first as it has an innovative waste management centre in which multiple recovery operations have been introduced and it hosts the first waste-to-biofuels venture in North America. Each of the other regions were analyzed to determine whether the production of biofuels by thermochemical conversion was a potential avenue of development, and if so, the driving factors and greatest barriers for development were identified. For cases where the framework yields an inconclusive analysis, there will be discussion on how the existing classification methodologies and operational strategies must adapt to facilitate further conversation on the topic of energy recovery from MSW.

2.4 Results and Discussion

2.4.1 Jurisdiction Background Statistics

The following information provides context on the population and climate of each Canadian jurisdiction under review. Table 2 summarizes the population, land area, population density and per capita MSW disposal for each of the jurisdictions. It is important to note that Edmonton, Saskatoon, and Toronto are designated as cities, while Halifax is designated as a regional municipality, which accounts for the larger land area, and Vancouver waste management is organized for the entire Metropolitan Area of Vancouver. Population density was calculated using the data for population and area from Statistics Canada (2016), while MSW disposed was calculated per capita based on the total tonnage of MSW disposed in each region listed in Table 2.8. Climatic variances influence the composition of the MSW collected at different times of the year. High moisture also makes handling and utilization of the waste more difficult and reduces the efficiency of utilization processes. Vancouver is the only region that does not typically experience sub-zero temperatures during the winter months; Edmonton, Saskatoon, and Vancouver experience high seasonal precipitation variances, while Toronto and Halifax experience high precipitation amounts throughout the entire year (Government of Canada 2017).

Table 2.2: Population and land area of Canadian jurisdictions under review.

Jurisdiction	Population [a]	Area [a] (km^2)	Population Density (no. of people/km^2)	MSW Disposed (kg/capita)
Edmonton, Alberta	932 546	685.25	1361	248
Halifax, Nova Scotia	403 131	5490.35	73	268
Saskatoon, Saskatchewan	246 376	228.13	1080	508
Toronto, Ontario	2 731 571	630.20	4334	187
Vancouver, British Columbia	2 463 431	114.97	21 427	234

[a] (Statistics Canada 2016)

2.4.2 Classification Review

2.4.2.1 Edmonton

The last complete characterization study for the City of Edmonton was conducted in 2001; the results of a waste audit organized in 2016 have yet to be reported. The purpose of this study was "to obtain a more accurate estimate of the composition of the City's MSW stream, based on the waste generator" (City of Edmonton 2001). The waste stream under investigation was the garbage collection, and does not include source separated recyclables. Variabilities in composition due to seasonal collection, neighbourhood income levels, and residential type (multi vs. single family) were accounted for in the study methods. Table 2.3 provides a summary of results for the percent composition by mass of different materials in the waste stream. The category list is concise and is broken down by material type. There is specific emphasis on biodegradable organics, likely due to the fact that this study was conducted at the time of construction of the Edmonton Composting Facility. The standard deviation for the average composition represents the seasonal variability for each material fraction.

Table 2.3: City of Edmonton waste composition summary (City of Edmonton 2001).

Material	June 2000 (%)	October 2000 (%)	January 2001 (%)	April 2001 (%)	Average (%)
Paper	10.02	12.79	25.21	16.40	16.11 (6.61) *
Food	15.57	24.94	34.65	21.47	24.16 (2.25)
Other Organics	7.55	8.58	12.61	8.47	9.30 (2.25)
Yard Wastes	49.84	30.05	0.49	32.56	28.24 (20.48)
Metal	2.04	3.79	3.25	2.23	2.83 (0.83)
Aluminum	0.29	0.76	0.89	0.70	0.66 (0.26)
Glass	1.03	1.52	4.37	1.46	2.10 (1.53)
Plastics	5.56	7.10	9.03	7.29	7.25 (1.42)
Textiles	2.51	2.86	3.24	3.12	2.93 (0.32)
Other Wastes	4.31	7.40	4.64	5.75	5.53 (1.39)
Household Hazardous	1.28	0.20	1.61	0.55	0.91 (0.65)

* Value in parentheses is sample standard deviation, where n=4.

Curbside collection of waste in the City of Edmonton consists of black bin and blue bag programs. Black bins are for disposal of all non-recyclable household garbage, as well as organic food and yard waste. Blue bags are used for collection of recyclable materials, including paper, cardboard, cans, glass, and plastics. There are collection centres for organic yard waste, as well household hazardous and bulky wastes. Waste management activities are localized at the Edmonton Waste Management Centre. Blue bag materials, accounting for 30% of the entire waste stream, are processed at a materials recovery facility. The garbage collected in the city is transferred to the Integrated Processing and Transfer Facility, wherein the compostable organic material is screen separated (smaller sized fraction) and conveyed to the onsite composting facility; this waste stream represents another 20% of all MSW. After separation, the remaining material is processed into refuse-derived fuel (RDF) fluff, which is used as a feedstock for a Waste-to-Biofuels plant operated by Enerkem at the EWMC. Up to 40% (140,000 Mg/yr) of the entire MSW collected can be processed into RDF, leaving the inorganic metal, glass, dirt, and rocks as the only materials that are landfilled. Edmonton therefore, has achieved a landfill diversion rate of 90% when at full operational capacity; 30% is recycled, 20% is composted, and 40% is processed into RDF-fluff. The City of Edmonton has been innovative and proactive in their waste management strategies, driven by the fact that there are no landfills that remain operational within the city limits.

While the most recent characterization study is outdated, the City of Edmonton expresses a clear explanation of how they classify waste; by utilization potential: specifically, it is classified based on a single stream waste source, in which the material components are measured, regardless of their origin. Specific emphasis at the time of the study was looking towards utilizing the organics fraction of the waste stream. Downstream waste management processes are of greatest interest to the City of Edmonton.

2.4.2.2 Saskatoon

Prior to implementing a city-wide curbside recycling collection program in 2013, the city of Saskatoon conducted a waste characterization study to establish a baseline data set to use in future analysis in those diversion programs being instituted. Another objective of this study was to provide data to use for future waste-to-energy research and feasibility studies for the city. The study methodology looked at single and multi-residential, as well as self-hauled and industrial, commercial, and institutional (ICI) waste streams. Other demographic variables included income variation and housing age. Seasonal variability was considered by conducting 2 sorts at different times of the year; September represents the end of the growing season, while November represents the winter season. A summary of the waste audit report is expressed in Table 2.4. Different categories were used depending on the waste stream, however, in each case the categories were product-based. The 2014 Integrated Waste Management Report indicated that 125,238 tonnes of waste were disposed of at the city’s landfill, approximately 50% comes from the residential collection (City of Saskatoon 2014).

Table 2.1: City of Saskatoon waste composition summary (HDR Corporation 2013).

Material	September (%)	November (%)	Average (%)
Curbside Residential Waste			
Food Waste	27.82	36.14	31.98 (5.88) [a]
Yard Waste	15.13	1.62	8.38 (9.55)
Paper	16.71	20.29	18.50 (2.53)
Plastics	12.77	11.92	12.35 (0.60)
Textiles and Fabrics	6.95	5.86	6.41 (0.77)
Metal	3.83	2.90	3.37 (0.66)
Diapers/Sanitary Products	4.32	4.93	4.63 (0.43)
Glass	1.40	1.99	1.70 (0.42)
Beverage Containers	1.24	1.02	1.13 (0.16)
HHW [b]	0.15	0.89	0.52 (0.52)
Wood (Painted/Treated)	2.83	0.18	1.51 (1.87)
Tissue Paper	2.82	4.80	3.81 (1.40)
Other	4.03	7.46	5.75 (2.43)
Self-Haul Residential Waste			
Paper	1.97	1.65	1.81 (0.23)
Plastics	3.61	2.63	3.12 (0.69)
Metal	5.49	0.78	3.14 (3.33)
Textiles and Fabrics	1.51	0.38	0.95 (0.80)
Yard Waste	11.99	0.00	6.00 (8.48)
Construction	19.42	24.14	21.78 (3.34)
Furniture	3.76	13.52	8.64 (6.90)
Carpeting	7.48	4.10	5.79 (2.39)
Wood (Painted/Treated)	40.81	20.79	30.80 (14.16)
Wood (Pallets)	0.27	21.69	10.98 (15.15)
Wood (Clean)	0.00	7.48	3.74 (5.29)
Other	3.69	2.84	3.27 (0.60)

[a] Value in parentheses is sample standard deviation, where n=2.

[b] HHW: Household Hazardous Waste

Currently the City of Saskatoon uses curbside bin collection for residential waste, recycling and organics. Black bins are used for household garbage, while blue bins are for recyclable paper, plastics, metals, and glass; each are collected biweekly during most of the year, with weekly black bin collection during the warmer months. Green bins for food and yard waste are available for subscription, with collection every two weeks during the growing season. The province of Saskatchewan also has an extensive beverage container deposit program which encourages recycling of plastic, glass and aluminum containers (City of Saskatoon 2017). Saskatoon operates a single landfill and two composting depots. The recycling program is contracted to an external company which collects the bin contents and completes processing at a materials recovery facility. The 2014 Integrated Waste Management Report stated that the landfill diversion rate had remained constant at 22.5% for over 2 years, and as such new strategies for reaching a diversion goal of 70% were needed (City of Saskatoon 2014). This currently low diversion rate is likely the reason for the alarmingly high disposal amount of MSW per capita (Table 2.2).

Based on the results of the characterization study the City of Saskatoon classifies their waste by product-type; while this provides a means of understanding the disposal habits of the region's residents, it does not provide a suitable framework for progressing diversion opportunities. This may be the reason for the stagnant, low diversion rates experienced by the city, despite efforts to increase awareness.

2.4.2.3 Vancouver

The Metro Vancouver area conducts regular characterization studies every three years for continued monitoring and as a metric for judging the success of their waste diversion goals. The most recent available report is for the 2013 study year. The methodology of these studies compares single and multi-family residential waste collection as well as ICI and self-haul sources, providing a thorough representation of the municipal waste stream. As with most studies, seasonal variation was considered by completing sorts during different times of the year. Table 5 provides a summary of the characterization report. The first six categories are material-based, and represent the proportion of the waste stream that could be diverted, either to recycling or composting. The remaining categories are product-based and represent composite wastes that many municipalities have set up separate collection programs due to safety or difficult handling.

Table 2.5: Vancouver 2013 waste composition by sector (Tetra Tech EBA Inc. 2014).

Category	Single-Family Residential	Multi-Family Residential	ICI [a] (%)	Self-Haul	Combined Average
Paper	12.2	10.5	18.1	5.7	13.6
Plastics	18.1	13.2	15.7	6.5	14.4
Compostable Organics	43.3	46.8	35.8	16.1	36.2
Non-compostable Organics	4.2	6.5	8.6	30.7	10.7
Metals	2.9	3.6	3.5	2.6	3.2
Glass	1.5	2.5	1.6	0.9	1.6
Building Material	3.6	4.1	6.2	26.8	8.4
Electronic Waste	0.8	2.6	0.8	0.9	1.1
Household Hazardous	1.0	1.2	1.0	0.3	0.9
Household Hygiene	11.2	6.6	3.0	0.1	5.0
Bulky Objects	0.3	1.8	5.1	9.3	4.1
Fines	0.8	0.6	0.6	0.2	0.6

* ICI: Industrial, Commercial, and Institutional

Metro-Vancouver is one of few jurisdictions that attempts a method of source separation in its collection program. Black bins are used for garbage, they come in multiple sizes and are collected by the city. Recycling collection is contracted to an external company by the city and is how source separation is implemented. Blue boxes are for plastics and metals, grey boxes are for glass containers, and reusable yellow bags are for paper and cardboard. Green bins have been implemented for food and yard waste, and similar to the black bins, come in different sizes (City of Vancouver 2017). The city has one transfer station and one landfill for disposal of MSW. Recycling is processed by the contracted company. A ban on disposing of food waste in garbage was legislated in 2015 to further help in increasing the landfill diversion (City of Vancouver 2015). The 2016 landfill report identified that 575,278 tonnes of MSW was disposed of at the landfill (City of Vancouver Engineering Services 2017).

Landfill diversion is the priority goal for the Metro-Vancouver area, with the aim to increase diversion to 80% by 2020 (City of Vancouver 2017). Compared to Edmonton, where processing operations have been implemented to utilize the waste once it reaches the waste management centre and keep it out of the landfill, Vancouver has placed emphasis on the role of its citizens in improving waste utilization. Between the source separated recyclables and the ban of food waste in garbage, the different waste streams can be more easily diverted to particular operations.

Overall, Vancouver classifies their waste based on collection requirements. The source separated recyclables and organics curbside programs are acknowledged, as well as products requiring specific handling centres, such as electronics and bulky objects. This framework is well suited for gauging the success of currently implemented diversion programs, but does not allow insight into alternative waste management technologies that could be implemented.

2.4.2.4 Toronto

The City of Toronto conducted a waste characterization study in 2012-2013 as an initial phase of its "Long Term Waste Management Strategy" project, of which the final report was released in 2016. The waste composition summary (Table 2.6) displays the sort categories that were used. The basis of these categories is a cross-over between material, product, and utilization potential. Each material is isolated, and further categorized into whether it is recyclable, indicating its utilization potential, or by its original product, in the case of glass. These categories help the understanding of the residents' disposal habits, as well as gauge the success of diversion programs.

Currently, the City of Toronto has implemented three bins – black, blue, and green – for its garbage, recyclables, and organics, respectively. Each bin type comes in multiple sizes, with the associated cost for each being a motivation for residents to reduce their disposal of wastes. Of the total 928,118 Mg of waste collected in 2015, 28% was collected from the blue bins and diverted to recycling facilities, and 28% was diverted to organic waste facilities via the green bins and yard waste collection sites (Toronto 2016). The only remaining landfill within the city accommodates the remaining 44%, and is utilized via seven transfer stations where the waste is dropped off and sorted. In 2015, approximately 510,000 tonnes if MSW was reported to have been disposed of at the landfill (Toronto 2016). There are 160 closed landfill sites under the care of the City of Toronto, displaying the impending need for diversion due to limited land space.

Table 2.6: City of Toronto 2010-2013 waste audit summary (HDR Corporation 2015).

Material	Single Family (%)	Multi-Residential (%)	Average (%)
Food Waste/Organics	38	55	46.5 (12) [a]
Yard Waste	3	3	3 (0)
Recyclable Paper	8	13	10.5 (3.5)
Non-Recyclable Paper	2	1	1.5 (0.7)
Recyclable Plastic	4	5	4.5 (0.7)
Non-Recyclable Plastic	14	8	11 (4.2)
Aluminum	1	1	1 (0)
Steel	1	1	1 (0)
Other Metal	2	1	1.5 (0.7)
Glass (Alcohol)	0.1	0.5	0.3 (0.3)
Glass (Food and Beverage)	1	1	1 (0)
Other Glass	1	1	1 (0)
Household Hazardous	0.5	0.4	0.5 (0.1)
Other [b]	25	10	17.5 (10.6)

[a] Value in parentheses is sample standard deviation, where n=2.

[b] Other: textiles, carpeting, kitchen appliances, wood, etc…

The completed long-term waste management strategy set the landfill diversion goal at 70% by 2026 (Toronto 2016). Their management plans are to further encourage waste reduction and utilization of diversion programs currently in place, while instituting technologies for extending these recycling and organics diversion programs into a circular economy.

The City of Toronto has managed to classify their waste stream based on material, in a way that also indicates the utilization potential of the waste. It highlights the existing diversion operations as well as where there is opportunity for new processing technologies.

2.4.2.5 Halifax

In 2011 a waste characterization study was conducted for the Halifax Regional Municipality (HRM) as phase one of an MSW energy conversion project. The purpose of the study was to "perform a detailed characterization of the residual waste stream" and from that determine further diversion opportunities and technologies. The study was extremely detailed with 3 levels of categorizing for the sort. The first level of separation was by material (i.e. plastic, paper, etc.), while the next subcategory was product-based and indicated the form of the material. Finally, each category was designated as whether it was acceptable for landfill or not; this indicated which materials already had an existing diversion program (i.e. recycling, composting, etc.). The methodology of the sort incorporated both residential and ICI waste sources, but did not consider seasonal variations in the waste composition. Table 2.7 provides a summary of the results from the 2011 study.

Table 2.7: Halifax Regional Municipality waste characterization summary (CBCL 2011).

Material Categories	Acceptable for Landfill Disposal?	2011 Average Composition (%)
Paper & Paperboard		
Dry newspaper	No	1.82
Dry corrugated cardboard	No	1.49
Pizza boxes	No	0.09
Magazines	No	0.99
Boxboard	No	4.72
Telephone books/directories	No	0.06
Fine paper	No	2.98
Polycoat deposit	No	0.04
Polycoat non-deposit	No	0.05
Wet newspaper	Yes	0.65
Wet corrugated cardboard	Yes	1.65
Waxed cardboard	Yes	0.36
Wallpaper	Yes	0.20
Other paper	Yes	0.62
Milk Containers		
All milk/soy containers	No	0.25
Glass		
Clear/coloured non-deposit containers	No	0.50
Glass beverage deposit containers	No	0.53
Windshield glass	Yes	0.00
Other glass	Yes	0.66
Metal		
Beverage deposit containers (ferrous)	Non	0.04
Food non-deposit containers (ferrous)	No	0.03
Aerosol (ferrous – empty container)	Yes	0.12
Paint cans and lids	Yes	0.06
Other ferrous	Yes	1.78
Composites (mostly ferrous)	Yes	3.01
Beverage deposit containers (aluminum)	No	0.14
Food non-deposit containers (aluminum)	No	0.57
Aerosol (aluminum – empty containers)	Yes	0.09
Foil (aluminum)	Yes	0.25
Other aluminum	Yes	0.22
Composites (mostly aluminum)	Yes	0.28

Material Categories	Acceptable for Landfill Disposal?	2011 Average Composition (%)
Plastic		
Beverage deposit containers (PET 1)	No	0.19
Non-deposit PET 1	No	0.42
Recyclable HDPE 2	No	0.72
Bags (PE)	No	2.61
Non-recyclable containers (#3, 4, 5, 6, 7)	Yes	2.63
Containers with contents	Yes	0.48
Polystyrene (foam)	Yes	0.50
Crates, pails, drums (>25L)	Yes	0.00
Stretch wrap	Yes	0.16
Shipping/courier bags	Yes	0.02
Soiled bags	Yes	3.45
Other plastics	Yes	2.35
Multi-Material Wastes		
Predominantly paper	Yes	0.69
Predominantly glass	Yes	0.13
Predominantly ferrous	Yes	1.02
Predominantly non-ferrous	Yes	0.78
Predominantly plastic	Yes	1.38
Other composites	Yes	0.75
Textiles		
Clothing/Towels/Sheets	Yes	11.94
Carpeting	Yes	2.42
Organics		
Food waste	No	11.33
Yard waste (grass clippings, leaves)	No	0.90
Bulky yard waste (branches)	No	0.05
Other organics	Yes	3.76
Special Care Wastes		
Batteries	No	0.05
Paint cans (with contents)	No	0.17
Solvent/aerosol cans (with contents)	No	0.48
Waste oil (containers, contents, and filters)	No	0.12
Sharps	No	0.00
Propane tanks	No	0.04
Other special care wastes	No	6.34
Bio-hazardous (first-aid, sanitary, diapers)	Yes	4.00
Tires		
Tires	No	0.00
Electronics	No	0.83
Other rubber	Yes	0.16
Construction & Demolition Renovation Wastes		
C&D renovation wastes	Yes	4.20
Wood waste (lumber)	Yes	3.48
Fines	Yes	0.00
Other unspecified	Yes	0.00

HRM operates a diverse residential waste collection program. Household garbage is collected biweekly and households are allowed a maximum of 6 clear bags which must be placed in a metal or plastic garbage can. Recycling is source separated to some extent; blue bags are used for recyclable containers (metal, plastic, glass), clear bags for paper, and corrugated cardboard is to be tied in bundles. Recyclables are collected weekly and biweekly for urban and rural areas respectively. During the months of July and August, green carts for food and yard waste are collected biweekly. The municipality operates one waste processing and disposal facility (landfill), a materials recovery facility, and 2 compost facilities. In 2015, 108,190 tonnes of MSW was disposed of at the municipal landfill (Copp 2015). They also have a household hazardous waste drop-off depot. In 2012, the HRM achieved a landfill diversion rate of 68%. HRM conducted the composition study as an initial phase in investigating solid waste conversion technologies, and continues to work towards the goal of increasing landfill diversion through new ventures.

Waste classification in Halifax is a very detailed, material-based framework. While it may be more extensive than necessary, it provides the greatest opportunity for pursuing alternative diversion technologies. All materials marked as unacceptable for landfill disposal have existing diversion programs, while the remainder represent materials that may be recovered by other means.

2.4.3 Suitability for Waste-to-Biofuels Development

The following section is a discussion on the results of applying the Adapa et al. (2006) MSW classification framework (Figure 2.1) for energy recovery to each jurisdiction under review. Table 2.8 summarizes the total tonnage that each jurisdiction currently reports as sending to landfill, and thus, this is the quantity that would be under investigation for waste-to-energy applications. A comparative analysis of the relative MSW fractions for each jurisdiction, separated by the categories set up by the Adapa et al. (2006) classification system, is reported in Figure 2.2.

Table 2.8: Total tonnage of MSW landfilled in the most recent reported year for each jurisdiction.

	Edmonton	Saskatoon	Vancouver	Toronto	Halifax
Total Tonnage (year)	231 685 (2012)	125 238 (2014)	575 278 (2016)	510 000 (2015)	108 190 (2015)

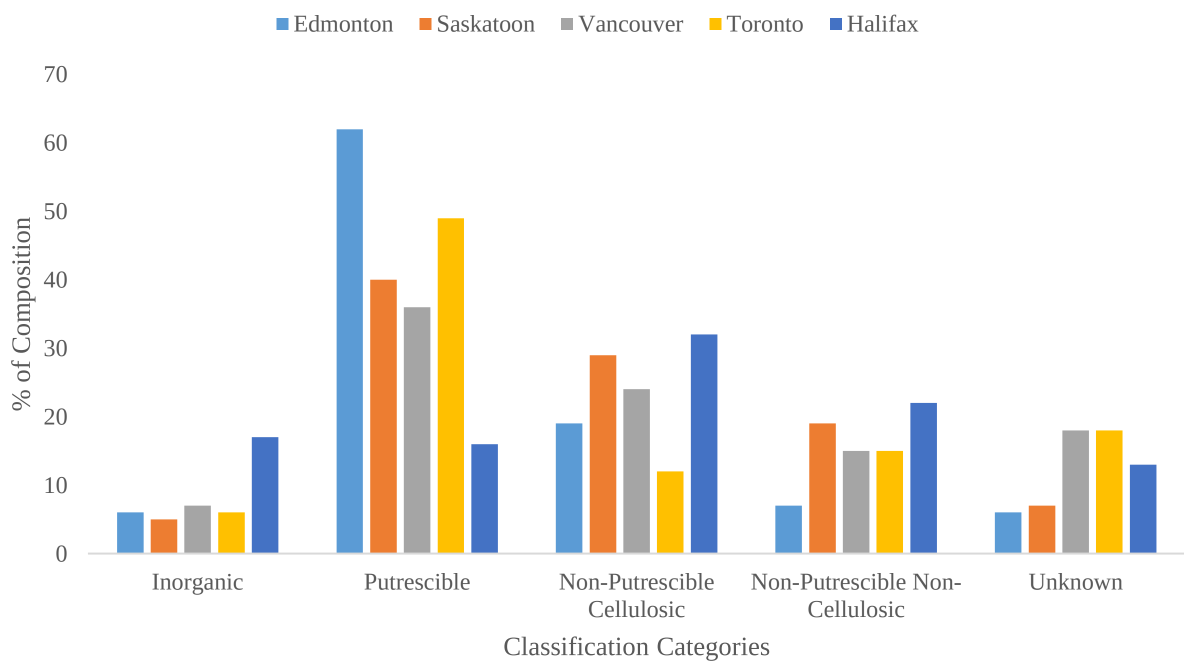

Figure 2.2: Composition summary of municipal solid waste fractions for waste-to-energy utilization following the Adapa et al. (2006) classification system for each jurisdiction.

2.4.3.1 Edmonton

The characterization study indicates that there is a significant portion of putrescible, organic material (food/yard waste) in the City of Edmonton's solid waste stream. The EWMC has justified a sorting method to separate this material from a single waste stream and divert it to an aerobic composting operation; an optional utilization method indicated by the Adapa et al. (2006) classification framework (Figure 2.1). The majority of the remaining material (paper, plastics, and textiles) is organic in nature, but not degradable, therefore, it can instead be subjected to gasification or pyrolysis to produce biofuels. In the case of Edmonton, they have collaborated with Enerkem to introduce a gasification operation to produce methanol and ethanol biofuels. Enerkem Alberta Biofuels converts 140,000 Mg of MSW refuse derived fuel per year. This choice in technology was to complement the composting facility that utilizes a large portion of the putrescible material, and to continue the City's goal to be innovative in the way that they management their waste. Any inert materials, such as metals and glass, represent inefficiencies for either technology, but can be removed from the waste before conversion and sent to landfill; overall this fraction accounts for very little of the waste. If the city did not have a composting facility, the waste stream could still be subjected to gasification, but there could be concern with high moisture impacting the conversion process. Edmonton's waste composition does not necessarily make it any better for gasification; the main reason for the Enerkem collaboration therefore, was to stimulate innovation.

2.4.3.2 Saskatoon

When the Adapa et al. (2006) classification framework is applied to the City of Saskatoon's waste management program, it is difficult to acquire a conclusive direction for suitable energy recovery technologies; the characterization categories are product-based and different depending on the source of the waste. The City has existing composting and recycling programs, both indicated as waste utilization methods for the appropriate materials. These programs should be developed further before pursuing larger thermochemical projects, however, planning for this type of technology in the future may be a wise choice.

2.4.3.3 Vancouver

Despite the fact that Metro-Vancouver waste collection is segregated into organics (which are already diverted to a composting recovery project), recyclables and other wastes, a significant portion is still organic in nature and could be thermo-chemically converted to biofuels. The compostable organics could pose a problem regarding high moisture content, but if existing green bin programs are utilized more due to the 2015 ban on food waste in garbage, this could be avoided. The parts of the characterization which are product-based, provide little information as to the material properties of the waste; this causes an uncertainty as to the amount of inert material that could reduce conversion efficiency and require further processing prior to utilization. The waste composition study (Table 2.5) indicates that over 300,000 Mg of MSW could be suitable for a biofuels feedstock, more than twice that which is converted by Enerkem; this indicates a sustainable feedstock source for a waste-to-biofuels operation. While waste-to-biofuels may be a feasible diversion and utilization opportunity, the Vancouver waste management goals are currently based on waste reduction and source diversion; thus, an alternate socio-political initiative regarding biofuels development would be required to justify this technology; an economic incentive for producing green energy could help in initiating this, by reducing the impact of cost on the decision making process.

2.4.3.4 Toronto

The material-based City of Toronto waste classification methodology melds with the Adapa et al. (2006) framework well, apart from a rather larger percentage of "other" wastes (Table 2.6) that are not clearly identified as to their material characterization. Until this category is further developed, that material is likely destined for landfill, along with the inorganic materials (glass and metals). Approximately half of the MSW is food or yard waste organics that is a suitable feedstock for biochemical conversion by composting, anaerobic digestion, or ethanol fermentation. There does remain a fraction of waste that is non-degradable, yet organic in nature (paper and plastics) that could be diverted for thermochemical conversion, however, the city's long-term waste management strategy did not decide to pursue waste-to-energy projects, and plans to promote waste reduction and proper improved utilization of existing programs. Should the city be encouraged to pursue a waste-to-biofuels venture, their framework for MSW classification would allow them to do that.

2.4.3.5 Halifax

The Adapa et al. (2006) classification framework is easily applied to the Halifax waste characterization study as it is very specific; further it identifies that materials that require new technologies for diversion, of which waste-to-biofuels may be one. Composting and recycle recovery operations already exist for the municipality, however, any residual food/yard waste or recyclable material that is not source-separated can be handled by thermochemical conversion. Of all the jurisdictions under review, Halifax is most likely to implement a waste-to-biofuels operation in the near future; the characterization study was specifically contracted for investigation into this diversion opportunity.

2.5 Conclusions

In conclusion to the review, multiple Canadian jurisdictions were analyzed as to how MSW is classified and the suitability for waste-to-biofuels development in each region.

1. Each jurisdiction utilizes either a material-based or product-based classification framework for their MSW. Material-based classification frameworks are more appropriate for investigating alternative waste utilization opportunities for improving landfill diversion.
2. Characterization studies were used either for monitoring of existing landfill diversion programs or for establishing new waste management strategies and assessing future development of thermo-chemical conversion programs.
3. Each of the jurisdictions has the possibility of pursing waste-to-biofuels development based on existing classification methodologies with minor adaptions, however, the greatest barrier is the lack of a socio-political driving incentive for producing biofuels to improve the city's environmental impact.

Chapter 3

3 Characterization and Compression/Relaxation Properties of Municipal Solid Waste Refuse-Derived Fuel Fluff

A version of this chapter consisting of only the compression and relaxation properties content has been published in the KONA Powder and Particle Journal:

- Sprenger, C., L.G. Tabil, and M. Soleimani. 2017. Compression and relaxation properties of municipal solid waste refuse-derived fuel fluff. *KONA Powder and Particle Journal* doi:10.14356/kona.2018005.

A version of this chapter consisting of only the compression and relaxation properties content was also presented at the 2016 CSBE Annual General Meeting and Technical Conference:

- Sprenger, C., L.G. Tabil, and M. Soleimani. 2016. Compression and relaxation properties of municipal solid waste refuse-derived fuel fluff, presented at the *CSBE/SCGAB 2016 Annual General Meeting and Technical Conference, Halifax, NS, July 3-6.* CSBE Paper No. 16-023.

Contribution of the MSc Candidate

The MSc candidate conducted literature review, planned and executed the pelleting experiments, applied the numerical models to the data sets, and prepared the manuscript for this investigation into the characteristics of MSW RDF fluff. Her research supervisor, Lope G. Tabil, provided guidance during planning of experiments and editorial advice during manuscript preparation. A researcher in the Chemical and Biological Engineering Department, Majid Soleimani provided guidance during planning of her experiments and assisted in setting up and running some of the pelleting procedures. The Catalysis and Chemical Engineering Laboratory conducted the CHNS ultimate analysis. The Feeds Innovation Institute laboratory at the University of Saskatchewan conducted the gross energy calorimetry tests for the biodegradable samples. The MSc candidate was trained and assisted by Tim Dumonceaux at the Agriculture and Agri-Food Canada, Saskatoon Research Centre to complete the fibre analysis.

3.1 Abstract

A characterization of the thermochemical and biochemical properties of municipal solid waste (MSW) refuse-derived-fuel (RDF) fluff was conducted to evaluate the suitability of MSW RDF-fluff for biofuels application. The ash content of RDF material was 19-39% while that of the biodegradable material samples was 20-23%. Proximate analysis resulted in a CHNS ratio of 33-41% carbon, 5-6% hydrogen, 0.6-0.8% nitrogen, and 0.2-0.5% sulfur for all samples. From the results of the proximate analysis, the higher heating value (HHV) for MSW RDF-fluff was calculated to be 14-16 MJ/kg. Fibre analysis of the biodegradable fraction determined that it contained 28% insoluble lignin, 1 % soluble lignin, 22% glucose, and 0% xylose.

As to the suitability of feedstock densification, the compression and relaxation characteristics of MSW refuse-derived-fuel RDF fluff were investigated with respect to biodegradable fraction, grind size, moisture content, applied load, and pelleting temperature. Experimental trials were performed by using a single pelleting unit mounted on an Instron universal testing machine. Two grind sizes of each sample were prepared, 3.18 mm and 6.35 mm, and moisture contents were conditioned to 8%, 12%, and 16% w.b. The applied loads were set at 2 kN, 3 kN, and 4 kN at two temperature settings, 50°C and 90°C. These parameter increments were selected based on literature values for similar experiments involving the pelleting of different biomass samples; moisture content was examined at higher levels than typical for other biomass to represent the moisture contents experienced by the City of Edmonton in their RDF production. The experimental data for these trials was collected and multiple compression and relaxation models were fitted to the applied pressure, compact density or volume data. The results indicated that the compact density of RDF was increased by increasing the grind size, while the compact density of biodegradable pellets increased with increasing pelleting load and temperature. The compact density of pellets produced from RDF ranged from 880-1020 kg/m^3; the compact density of the biodegradable pellets ranged from 1120-

1290 kg/m^3. The Walker and Jones models both indicated that the biodegradable material fraction has a higher compressibility than the RDF material, where neither moisture content nor grind size had a significant effect on the compressibility of either material. The Kawakita-Lüdde model estimated the porosity of the pelleted samples, while the Cooper-Eaton model indicated that the primary mechanism of densification was particle rearrangement. Application of the Peleg and Moreyra model for analysis of relaxation properties of the compressed materials determined the asymptotic modulus of the residual stress to be between 89 and 117 MPa for all experimental parameters; however, the RDF material produced more rigid pellets than the biodegradable material.

3.2 Introduction

In an age of societal dependence on fossil-based resources, paired with concerns over environmental sustainability, researchers and policy makers are avidly looking towards biofuels as an alternative means to meet the demand for energy in future generations. In particular, 'advanced' biofuels – those that are made with materials that do not compete with food or land resources – are of high research and development interest as a means to achieve the energy goal in the most sustainable means possible (BioFuelNet 2015). Biofuels are recognized as being carbon-neutral, slowing the exponentially rising consequences of greenhouse gas emissions, and are developed from renewable resources.

Municipal solid waste (MSW) consists of both organic and inorganic fractions and may include paper, plastic, glass, metal, food waste, wood, and other composite materials (Mor et al. 2006). There is potential for the utilization of MSW in the form of refuse derived fuel (RDF) as a feedstock for thermochemical conversion in this advanced biofuels industry. Typically, MSW is disposed of in landfills as garbage, as such the conversion to RDF would provide a more sustainable alternative disposal method for the waste. The City of Edmonton in collaboration with Enerkem Alberta Biofuels currently operates a Waste-to-Biofuels facility in which processed MSW (RDF-fluff) is converted into methanol through patented, low-severity gasification technology (EWMC 2015). Densification of this RDF-fluff would produce a higher quality feedstock that is more durable, improving storage and handling as well as providing a more uniform product for conversion. Establishing baseline data for the energy content, higher heating value (HHV) of RDF-fluff would also provide information for expanding MSW as waste-to-energy feedstock.

Literature indicates that there are numerous variables that influence biomass densification; these include both process conditions and material characteristics. The process variables imposed on the densification procedure include temperature, applied pressure, hold time, die geometry, and application rate. The addition of heat results in a reduced resistance to applied load by biomaterials (Sokhansanj et al. 2005). Increased applied pressure will indeed result in higher densities, however there is an optimal pressure that should be utilized at which the mechanical strength of the material due to plastic deformation is reached (Yaman et al. 2000). Hold times are most significant in reducing the effect of 'spring-back' from elastic deformation during compression; this parameter can be controlled during bench-scale pelleting experiments, however hold times in industrial pellet mills are more related to how well the material moves through the system. Die geometry influences the amount of material that can be pelleted; smaller diameters will increase the restriction and therefore the power required to produce a pellet. Material variables such as moisture content, particle size distribution, biochemical composition, and pretreatment are characteristic of particular biomass feedstocks. Several sources indicate that moisture contents between 8-12% result in denser and higher quality pellets from cellulosic materials (Sokhansanj et al. 2005). Water acts as a binder in which the contact area of the particles is increased, allowing for the formation of bonds by van der Waal's forces (Mani et al. 2003). Particle size distribution in addition to geometric mean diameter have an effect on the quality and density of pellets (Payne 1978). The biochemical composition of a feedstock (i.e. the fraction of starch, cellulose, protein, etc…) will also affect the densification process and may indicate the necessity for pretreatment such as is the case of lignocellulosic materials which are very resistant to deformation. Knowledge of the effects of these characteristics will assist in designing energy efficient compaction methods to produce high quality pellets for thermochemical conversion and provide understanding for the implementation of feasible waste management strategies.

Various models have been adapted in previous studies to examine the compression and relaxation characteristics of biomass feedstocks. The Jones, Walker, Kawakita-Lüdde, and Cooper-Eaton models are fitted to experimental compression data, while the Peleg and Moreyra model is fitted to relaxation data to determine a material's asymptotic modulus (Adapa et al. 2010). The relationship between compression pressure and compact density, from both Walker's and Jones' models, indicates the compressibility of a material and points to an optimal pelleting pressure to be used for energy-efficient compaction of different samples (Mani et al 2006). Porosity of compacted samples estimated using the Kawakita-Lüdde model allow comparison to the solid density of the loose material; the solid density is the maximum value that can be achieved during compression where there is zero porosity. The Cooper-Eaton model hypothesizes the mechanisms of densification as particle rearrangement and deformation and that if the sum of these two parameters do not result in unity, then there must be another mechanism involved in the compaction process; thus, analysis of these parameters can assist in determining the ratio of the mechanisms involved in the densification of new materials (Adapa et al 2010). A material's asymptotic modulus, estimated by the Peleg and Moreyra model, implies a material's ability to sustain unrelaxed stresses or its rigidity (Talebi et al 2011). A material with a high compressibility resulting in a highly compact, rigid pellet is the desired outcome of a densification process, thus analysis of these parameters can result in optimizing the conditions for pelletization.

The first objective of this study was to determine a baseline characterization of the thermochemical and biochemical properties of MSW RDF-fluff. The second objective of this study was to investigate how composition, grind size, moisture content, applied load, and processing temperature affect the compression and relaxation characteristics of MSW RDF-fluff.

3.3 Materials and Methods

3.3.1 Materials

Municipal solid waste (MSW) refuse-derived fuel (RDF) fluff was supplied by the Edmonton Waste Management Centre (EWMC), Edmonton, AB, Canada. The fluff upon receipt had a moisture content of 5.5% wet basis (w.b.) and an average bulk density of 54.6 kg/m^3. It is to be noted that the EWMC facility experiences RDF-fluff moisture contents of upwards of 20-30% w.b. Moisture content was measured by placing approximately 5 g of the original sample in an oven at 105°C overnight, after which the change in mass was recorded and the wet basis moisture content was calculated; three replicates were made to determine the average moisture. The bulk density of the received MSW-RDF fluff sample was measured using a 5850 mL (cm^3) container; six replicates were completed to account for the heterogeneity of the material.

Pelleting characteristics were examined for two different fractions of the RDF-fluff material. The first material utilized the RDF in its raw composition; this consisted of approximately 35% paper, 22% plastics, 14% textiles, 6% wood/organics, and the remainder fines and inerts, determined by a composition sort. The second material consisted of only biodegradable components, wood and paper, after undergoing sorting to remove plastics and textiles.

Each material was ground in two screen sizes, 3.18 mm and 6.35 mm, using a knife mill (Retsch GmbH, Haan, West-Germany). The moisture content of each of the 4 material/grind size samples was determined according to ASABE Standard S358.3 (ASABE 2008), then adjusted to 8%, 12%, and 16%, w.b. Samples were allowed to equilibrate in air-tight containers for a minimum of 3 days prior to the start of the experiment.

Prior to the experiments, the particle density of each material was determined for each moisture content and grind size combination using a pycnometer (Multipycnometer, Quantachrome Corp., Boynton Beach, FL); particle density is the maximum compact density that can be achieved during compression.

3.3.2 Characterization

For comparison to other biomass and fuel pellet options, a characterization of thermochemical and biochemical properties of the MSW RDF-fluff samples was conducted. Ash content influences the energy content of a feedstock and thus the efficiency of a conversion process. Proximate analysis and gross energy bomb calorimetry were used to calculate the higher heating value of the MSW-RDF-fluff samples.

Thermochemical analyses were conducted on pellet samples produced during a pilot-scale pelleting trial. The pilot-scale pelleting process was implemented to further evaluated the parameters optimized during the single-pelleting unit trials described in section 3.3.3. The samples therefore, were the RDF material with and without preheating, and the biodegradable material with preheating, each ground with a screen size of 6.35 mm and conditioned to an initial moisture content of 16% w.b.

A fibre analysis, typically done on purely plant biomass samples, was conducted to investigate the carbohydrate availability for ethanol fermentation conversion processes in the biodegradable sample.

3.3.2.1 Ash Content

Ash content for each sample was determined by the NREL standard: determination of ash in biomass (Sluiter et al. 2008). Approximately 1-2 g of pellets, sliced to increase surface area, were first dried at 105°C overnight to remove any moisture from the material. The material was then subjected to incineration in a furnace at 575 ± 25°C for 24 ± 6 h. Crucibles containing the ash sample were then placed in a desiccator to cool. Weight measurements were recorded for the empty crucible and for the crucible containing the sample before drying, before incineration, and after incineration. Three replicates were conducted for each sample. Percent ash was calculated by the following equation:

$$\%\ Ash = \frac{Weight_{crucible\ plus\ ash} - Weight_{crucible}}{Weight_{crucible\ plus\ dried\ sample} - Weight_{crucible}} \tag{3.1}$$

AK-2 (US Patent No. 7,785,379 B2; August 31, 2010) is used as a fuel additive that helps to raise the fusion point of inorganic elements in the sample and to reduce volatile emissions (Emami et al. 2014). This was added at 0.15% by mass or omitted for each of the samples prepared for thermochemical characterization. Its effect on the ash content of each sample was investigated.

3.3.2.2 Ultimate Analysis and Higher Heating Value (HHV)

Ultimate analysis was completed to determine the carbon, hydrogen, nitrogen, and sulfur content in each of the pellet samples. This analysis was performed by the Catalysis and Chemical Engineering Laboratory at the University of Saskatchewan.

For the biodegradable material samples, gross energy calorimetry was done to determine the higher heating value of the pellets. This analysis was conducted by the Feeds Innovation Institute Laboratory at the University of Saskatchewan. The method used was with a Parr Instruments 6400 calorimeter (Parr Instruments, Moline, IL). This analysis was not available for the RDF pellet samples due to the plastic fraction of the material; the equipment requires a particular halogen-safe container to complete the test which is not possessed by any laboratory facilities available to us.

In response to the unavailability of experimental analysis for the determination of gross energy, a numerical model was used to determine the higher heating value (HHV) of the RDF pellet samples. Freidl et al. (2005) theoretically determine HHV of a biomass sample based on ultimate or elemental (C, H, N, and S) composition of the sample (Eq. 3.2). These models were verified using the experimental values of gross energy for the biodegradable material pellet samples.

$$HHV(MJ/kg) = 3.55C^2 - 232C - 2230H + 51.2CH + 131N + 20600 \tag{3.2}$$

3.3.2.3 Organic Components Analysis

In order to determine the suitability of MSW RDF-fluff for biochemical conversion processes, a fibre analysis was completed. The analysis was completed with guidance from Tim Dumonceaux at the Agriculture and Agri-Foods Canada Saskatoon Research Centre; the protocol followed was modified from the NREL laboratory procedure titled, "Determination of structural carbohydrates and lignin in biomass" (Sluiter et al 2007). The analysis provides percent content of insoluble lignin, soluble lignin, xylose (hemicellulose), and glucose (cellulose). It was anticipated that the insoluble lignin content would be grossly exaggerated due to the remaining plastic and inorganic fractions that are present in the sample.

3.3.3 Compression and Relaxation Tests

The compression tests were performed using a single pelleting unit (SPU) apparatus mounted on an Instron Universal Testing Machine (Model No.3366, Instron Corp., Norwood, MA). This SPU consisted of a cylindrical die fixed to the base of the machine with a plunger attached to the moving crosshead of the Instron machine (Shaw 2008). A heating element was attached to the pelleting die in order to control the temperature of the process; the effect of two different temperatures (50°C and 90°C) was assessed, with the pelleting protocol allowing time for the material to preheat in the die before being compressed. Approximately 0.55 ± 0.05 g of biomass was fed into the die to produce each pellet. The Instron was then used to apply the load to compress the charged material at a rate of 50 mm/min until the desired compressive force (2, 3, and 4 kN) was achieved, at which point the plunger was held for 60 s as a retention time to avoid "spring-back" typical of densified biomass. A gate in the platform of the SPU apparatus was then opened manually to allow the plunger to eject the newly formed pellet from the die. The software programmed to control the Instron and complete the densification process recorded the time and force-displacement data for each pellet. Twelve pellets (replicates) were produced for each treatment combination; the dimensions and mass of each pellet was measured after each pellet was stored at room conditions for subsequent analyses.

3.3.3.1 Data Analysis

The experimental data collected was analyzed using several compression and relaxation models for powders. All of the models were fitted to the experimental data using Microsoft Excel (Microsoft Corp., Redmond, WA) with the exception of the Cooper-Eaton model, in which SAS (Statistical Analysis System, Cary, NC) was employed. The Microsoft Excel analysis incorporated the solver tool and non-linear regression techniques, in which constants for the appropriate models were determined for each set of experimental data by the method of least squares. Acceptability of the correlation between the model constants and the experimental data was determined by the mean square error and the coefficient of determination (R^2) of the respective models.

The purpose of fitting the compression and relaxation data of the densification experiments was to determine the relationship between compression pressure and compact density in order to determine the most energy-efficient means of producing quality pellets for different material conditions.

Models proposed for analyzing the compressibility of powders have also been successfully applied to the compression of biomaterials such as timothy hay. Compression of non-metallic powders were modelled by Walker according to the volume ratio to applied pressure (Eq. 3.3) (Walker 1923).

$$\frac{V}{V_s} = m \cdot \ln P + b \tag{3.3}$$

Where, V = volume of compacted hay, m^3; V_s = void-free solid volume, m^3; P = applied pressure, MPa; m, b = constants.

Jones (1960) described the compression of industrial metal powders through the linear relationship of the natural logarithm of both pressure and density (Eq. 3.4).

$$\ln \rho = m' \cdot \ln P + b' \tag{3.4}$$

Where, ρ = compact density, kg/m^3; m', b' = constants.

Kawakita and Lüdde (1971) related pressure to the volume reduction of metallic powders (Eq. 3.5).

$$\frac{P}{C} = \frac{1}{a_1 b_1} + \frac{P}{a_1} \tag{3.5}$$

$$C = \frac{V_0 - V}{V_0} \tag{3.6}$$

Where, C = volume ratio; V_0 = initial volume at zero pressure, m^3; a_1, b_1 = constants.

Cooper and Eaton (1962) attributed the compression of ceramic powders to two independent processes; the filling of large voids through material sliding past one another and slight fractures followed by the filling of small voids through plastic flow and fragmentation (Eq. 3.7).

$$\frac{V_0 - V}{V_0 - V_s} = a_2 e^{\frac{-k_1}{P}} + a_3 e^{\frac{-k_2}{P}} \tag{3.7}$$

Where, a_2, a_3, k_1, k_2 = constants.

The relaxation characteristics of solid foods are modelled by Peleg and Moreyra and can be used to compare different materials (Eq. 3.8).

$$\frac{F_0 \cdot t}{F_0 - F(t)} = k_3 + k_4 \cdot t \tag{3.8}$$

Where, F_0 = initial relaxation force, kN; F(t) = relaxation force at time t, kN; t = time, s; k_3, k_4 = constants.

A modified model by Peleg and Moreyra (1980) gives a slope index that describes the solidity of compressed materials; this can be used to determine the asymptotic modulus of solid foods and powders. The asymptotic modulus is defined as the ability of the compressed material to sustain un-relaxed stress, represented by the residual stress in the Peleg and Moreyra model (Eq. 3.9).

$$E_{\mathrm{A}} = \frac{F_0}{A_{\mathrm{a}} \varepsilon}\left(1 - \frac{1}{k_4}\right) \tag{3.9}$$

Where, E_A = asymptotic modulus, MPa; ε= strain; A_a = cross-sectional area, m^2.

The percent average relaxation was calculated by using the initial force at the beginning of the relaxation phase and the final force after an elapsed time of 60 s (Eq. 3.10).

$$Percent\ average\ relaxation = \frac{100\times(F_0 - F_e)}{F_0} \tag{3.10}$$

Where, F_e = final relaxation force, kN.

3.4 Results and Discussion

The moisture content of the unprepared samples was determined to be 5.45% w.b. for the RDF material and 7.15% w.b. for the biodegradable fraction of the RDF material; these values were used to condition the samples, using the standard ASABE S358.3, to experimental moisture contents of 8, 12, and 16%. Moisture content had little significance over the particle density; however, the densities for RDF ground by 3.18 and 6.35 mm screens were approximately 1350 and 1280 kg/m^3, respectively, while the particle densities for biodegradable material ground by 3.18 and 6.35 mm screens were approximately 1230 and 1140 kg/m^3, respectively.

3.4.1 Thermochemical Characterization

Ash content, elemental composition, gross energy calorimetry, and numerical models were used to complete a thermochemical assessment of the pellets produced during pilot-scale pelleting.

Ash content of all samples were well above the maximum 1% by mass required to be considered a first quality fuel pellet; this is likely due to the 'dustiness' of the material and consistent with past examination of RDF pellets (NETL 2015). In the RDF samples, it is evident that AK-2 may indeed have an effect on reducing the ash content, although further investigation would be required to quantify the extent of the effect.

Knowledge of a sample's ultimate/elemental composition provides the ability to theoretically determine its energy value. CHNS analysis determined that carbon accounts for approximately 40% of each of the pellet samples by mass; also present is about 6% hydrogen by weight and less than 1% each nitrogen and sulfur by weight. The unaccounted mass can be attributed to oxygen and inorganic materials that are represented by the ash value indicated in Table 3.1.

Gross energy was measured for the two biodegradable material pellet samples as indicated in the methods. The average gross energy was 15.6 MJ/kg for the two samples. The higher heating value (HHV) was determined to be 14 – 16 MJ/kg for all samples using the Freidl, et al. (2005) model. These values were verified using the experimental gross energy measurements for the two biodegradable material pellet samples; the percent error was less than 3% for each sample, thus the model can be used for this application. These values for HHV are consistent with that presented by Freidl, et al (2005) in which waste was calculated to have an HHV value of 15.97 MJ/kg.

Table 3.1: Thermochemical characterization of municipal solid waste refuse-derived fuel fluff.

Sample	Ash Content (%)	Proximate Analysis				Measured Gross Energy (MJ/kg)	Calculated HHV (MJ/kg)
		Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulfur (%)		
RDF: 16 % m.c No preheating 0% AK-2	39.4 (1.5) [a]	32.77	4.90	0.72	0.47	-	14.20
RDF: 16 % m.c No preheating 0.15% AK-2	19.1 (1.3) [c]	40.93	6.25	0.80	0.47	-	16.32
RDF: 16 % m.c Preheating at 50°C 0% AK-2	28.2 (1.2) [b]	40.67	6.23	0.78	0.32	-	16.22
RDF: 16 % m.c Preheating at 50°C 0.15% AK-2	26.5 (1.1) [b]	41.20	6.21	0.75	0.28	-	16.42
Biodegradables: 16 % m.c Preheating at 50°C 0% AK-2	19.7 (3.1) [c]	39.99	5.93	0.65	0.26	15.57	16.00
Biodegradables: 16 % m.c Preheating at 50°C 0.15% AK-2	22.9 (0.2) [c]	39.85	5.91	0.57	0.20	15.65	15.95

[a] Value in parentheses indicates the standard deviation where n=3.

[b-c] Means without a common superscript letter differ ($P < 0.05$), as analyzed by one-way ANOVA.

When comparing the variation of HHV between samples, only the RDF sample produced with no preheating and no added AK-2 appears to be affect by the treatment, as p = <0.1.

3.4.2 Organic Components Analysis of the Biodegradable Fraction of Municipal Solid Waste Refuse-Derived Fuel Fluff

The results of the organic components analysis (Table 3.2) summarize the lignocellulosic composition of the biodegradable material. As anticipated, the insoluble lignin content is very large; this can be attributed to the heterogeneous nature of RDF and the inability to perfectly segregate the plastic and inorganic fractions from the biodegradable fraction. There was no quantifiable xylose in the sample, indicating no hemicellulose present in the material; this is likely due to the higher amount of processed biomass relative to raw biomass (yard waste). The glucose level is very low when compared to other lignocellulosic biomass such as hardwoods, wheat straw, and switchgrass at values of 40-55%, 30%, and 45% respectively (Bajpai 2016). Therefore, it can be concluded that at this time, a biochemical means of conversion of MSW RDF-fluff to biofuels, such as ethanol fermentation, is not a feasible means at this time based solely on the very low carbohydrate content of the biodegradable fraction.

Table 3.2: Organic components of the biodegradable sample.

	Lignin		Carbohydrates	
	Insoluble (%)	Soluble (%)	Xylose (%)	Glucose (%)
Mean	27.76	1.1	0	21.66
Std. Dev.*	3.05	0.1	0	2.64

* Standard deviation where n=3.

3.4.3 Compact Density

Table 3.3 shows the effects of material grind size, moisture content, pelleting load and temperature of the RDF and biodegradable materials, respectively. Compact density of the RDF pellets was only affected by the material grind size, in which the material ground in a 6.35 mm screen in the knife mill resulted in greater compaction. Compact density of the biodegradable pellets increased with increasing pelleting load and temperature, while there was no effect of moisture content or grind size of the material. There were however, differences in the compact density of the two materials; the biodegradable material produced high density pellets; 1100-1250 kg/m^3, at all applied pressure and temperature combinations, while the RDF material produced pellets with densities of 850-1000 kg/m^3. Bulk density of the pellets produced during the single-pelleting trial was unable to be measured due to the small sample size, however a bulk density of pellets produced in a subsequent pilot-scale trial was determined to be approximately 590 kg/m^3 and 660 kg/m^3 for RDF and biodegradable materials respectively. The bulk density of the raw RDF-fluff was 55 kg/m^3, therefore both the RDF and the sorted biodegradable materials produced a feedstock that was at least 10 times denser than the original product following pelletization.

Table 3.3: Effects of pelleting parameters on compact density (kg/m^3) of refuse derived fuel fluff and biodegradable material fraction.

Grind Size (mm)	Moisture Content (% w.b.)	Applied Load (kN) 2		3		4	
		Die Temperature (°C)					
		50	90	50	90	50	90
Refuse Derived Fuel Fluff							
3.18	8	938 (34)*	885 (28)	887 (32)	887 (34)	918 (47)	926 (37)
	12	898 (40)	870 (33)	896 (20)	913 (17)	937 (24)	929 (19)
	16	905 (20)	923 (40)	915 (23)	938 (19)	926 (13)	930 (45)
6.35	8	950 (36)	972 (36)	993 (47)	1000 (41)	1010 (29)	1010 (48)
	12	988 (44)	979 (40)	989 (49)	998 (42)	1007 (58)	990 (35)
	16	982 (36)	1014 (40)	991 (39)	1018 (34)	993 (59)	1010 (28)
Biodegradable material							
3.18	8	1126 (15)	1134 (21)	1194 (27)	1218 (18)	1206 (28)	1237 (22)
	12	1179 (19)	1190 (19)	1199 (12)	1232 (24)	1235 (22)	1250 (34)
	16	1154 (15)	1175 (13)	1194 (29)	1217 (16)	1219 (17)	1254 (29)
6.35	8	1122 (15)	1155 (38)	1181 (27)	1199 (14)	1253 (25)	1285 (18)
	12	1135 (25)	1184 (33)	1189 (29)	1227 (19)	1233 (23)	1255 (14)
	16	1161 (30)	1182 (20)	1204 (36)	1217 (21)	1227 (18)	1242 (21)

[a] Value in parentheses indicates the sample standard deviation where n=12.

3.4.4 Compression Models

The relationship between pressure, volume, and density of the RDF and biodegradable material during the compression portion of the tests (i.e. until maximum loading was achieved) were fitted to models that have been developed for powders. The Walker model describes the relationship of volume ratio to pressure, which decreases linearly as the pressure increases. All test combinations resulted in a fitted Walkers' model that yielded an average coefficient of determination value (R^2) of greater than 0.90 (Appendix: Table A.1). Figure 3.1 shows a sample relationship between the volume ratio and the natural logarithm of applied pressure. The slope, m, of the fitted Walker model is referred to as the compressibility constant and it did not vary much between all parameter tests for each material type. For RDF samples, the slope had an average value of -0.3197 with a standard deviation of 0.0194; while the biodegradable fraction of RDF had an average slope value of -0.3410 with a standard deviation of 0.0235. The biodegradable samples showed a higher slope (absolute value) indicating higher compressibility than the RDF material. This variation could probably be attributed to the different compression properties of the additional plastic fraction in the RDF material. The value of 'b' was greater at lower grind size and for the RDF material.

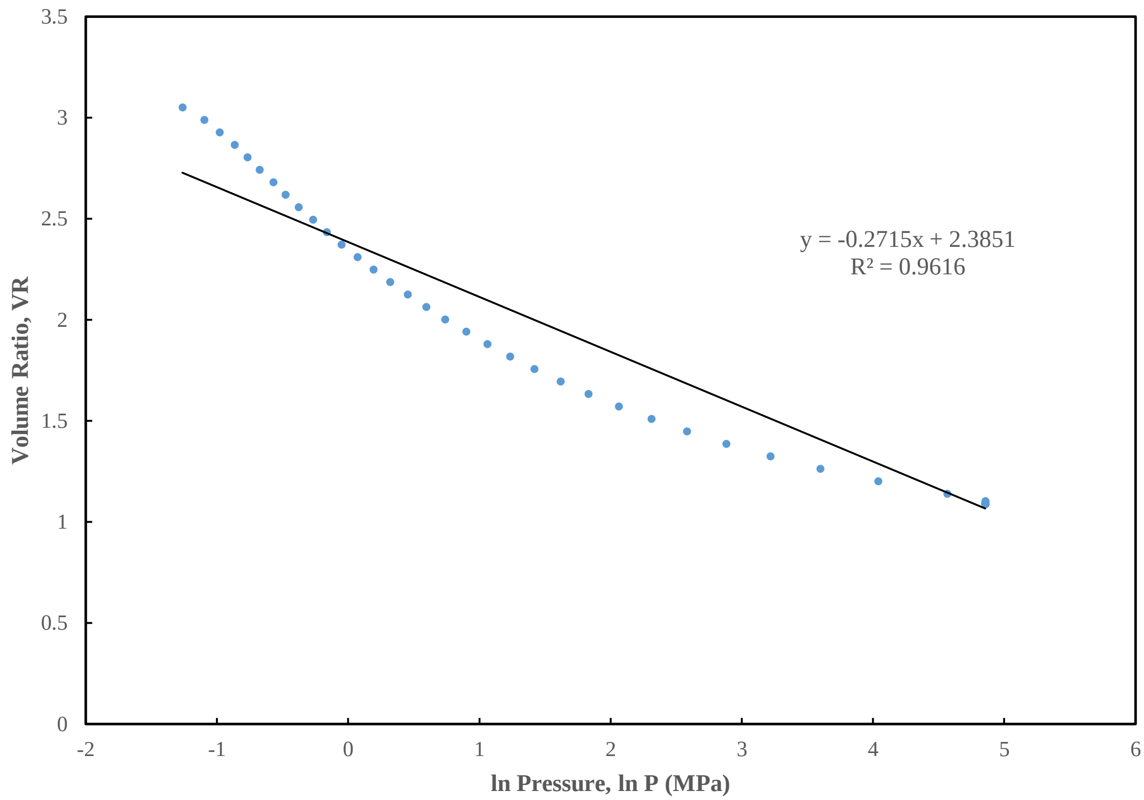

Figure 3.1: Fitted Walker model relationship to compression data for 3.18 mm, 16% m.c. biodegradable material under pelleting conditions of 4 kN applied force and 50°C die temperature.

The Jones model describes the relationship of compact density to pressure, which increases linearly as the pressure increases. All test combinations resulted in a well-fitted Jones' model, yielding an average R^2 value of greater than 0.97 (Appendix: Table A.2). The values of the slope, m', for the model indicates the compressibility of the material. For RDF samples, the slope had an average value of 0.1644 with a standard deviation of 0.0084; while the biodegradable samples had an average slope value of 0.1906 with a standard deviation of 0.0079. Similar to the results of the Walker model, the biodegradable samples showed a higher slope (m') indicating higher compressibility than the RDF material. For all moisture content/grind size combinations, the value of the slope appeared to decrease with an increase in either pelleting conditions, temperature or applied load. There was little difference in compressibility between trials with different material conditions, moisture content or grind size. The value of b' of the Jones model was relatively constant for all tests for both RDF and biodegradable materials at an average (standard deviation) of 7.2331 (0.1611) and 7.5622 (0.1509), respectively.

Fitting of the Kawakita and Lüdde model to the data, resulting in mean square error (MSE) values of less than $5x10^{-4}$ (Appendix: Table A.3), indicated a good fit. However, there was no correlation found between the model constants and any of the experimental variables for either material. Established by Kawakita and Lüdde (1971), the model constant a1 represents the initial porosity of the sample, while the parameter $1/b_1$ indicates the yield strength or failure stress of the compaction process (MPa). As such, the model indicates a higher average initial porosity for RDF material at a grind size of 6.35 mm, 0.899 compared to 0.753 at the 3.18 mm grind size. This is reasonable as the smaller particles would exhibit greater mechanical interlocking and thus, a lower initial porosity. The opposite observation is made for that of the biodegradable material, in which the model determined porosities of 0.801 and 0.772 for grind sizes of 3.18 mm and 6.35 mm respectively. This contradiction may be attributed to the fact that while the materials were ground using a particular screen size, not all of the particles were exactly the same size; a particle size analysis indicated that the biodegradable material, once ground, consisted of a higher fraction of fine particles than the equivalent RDF ground material. Decrease in grind size resulted in a decrease in the yield stress ($1/b_1$) for both the RDF and biodegradable material, however the actual values (standard deviation) were similar at 2.59 (0.61) kPa and 2.65 (0.60) kPa respectively.

The Cooper-Eaton model indicates that the two likely mechanisms involved in densification were particle rearrangement and deformation. The constants a_2 and a_3 in the Cooper-Eaton model, respectively represent the two mechanisms. Fitting the model to the experimental data yielded values for a_2 ranging from 0.66 to 0.97 and values for a_3 ranging from 0.00 to 0.23; this indicates that the majority of the compaction mechanism is as a result of particle rearrangement by the filling of large pores. The R^2 values for each sample were above 0.86 with most being at least 0.95, indicating a good fit of the model to the experimental data (Appendix: Tables A.4 and A.5).

3.4.5 Relaxation Characteristics

After the desired compression pressure was reached through the applied loading, the relaxation characteristics were observed for all trials. Noticeable relaxation was observed during the 60 s holding period; this indicates that complete plastic deformation was not fully achieved upon the applied loading.

The Peleg and Moreyra model was fitted to the linearized data of compressive pressure in relation to relaxation time (Appendix: Table A.6). The slope of the model, k_4, is referred to as the solidity index and was used to calculate the asymptotic modulus, E_a, for the material. The asymptotic modulus indicates a materials ability to sustain unrelaxed stresses, such that a higher E_a leads to a more rigid restraint of a pellet’s compact density (Table 3.4). Pellets produced from RDF material resulted in an asymptotic modulus of between 94 and 117 MPa, while the biodegradable pellets had an E_a value of 89 to 103 MPa. This indicates that the RDF material produces a more rigid pellet than the biodegradable material. The combined effects of pelleting temperature and initial moisture content have a positive correlation with the asymptotic modulus value for each material. Pellets produced at 90°C had E_a values 3 to 17 percent larger than those produced at 50°C; the highest percent difference was observed at 16% m.c. (w.b.) for each grind size. The asymptotic modulus values calculated for the RDF-fluff samples were comparable to other biological materials according to literature; for example, corn stover, barley straw, and wheat straw display E_a values between 20 and 160 MPa (Mani et al. 2006).

As previously noted, relaxation was observed during the experiment and was quantified as the percent average relaxation (PAR) (Table 3.5). Values ranging from 21 to 35% and from 29 to 37% were determined for the RDF and biodegradable pellets, respectively. These values are consistent with literature values for timothy hay, wherein PAR values of 27 to 53% were published (Talebi, et al. 2011). As with the asymptotic modulus, die temperature has the highest positive correlation to PAR.

Table 3.4: Effects of experimental variables on asymptotic modulus, E_a (MPa).

Grind Size (mm)	Temperature (°C)	Moisture Content (% w.b.)		
		8	12	16
Refuse Derived Fuel Fluff				
3.18	50	102.31 (2.06) *	94.33 (1.45) [a]	100.28 (9.40) [a]
	90	105.91 (0.98) [a]	99.76 (1.57) [b]	117.99 (3.92) [a,b]
6.35	50	102.92 (1.06) [a]	100.24 (4.68) [a]	102.26 (8.68) [a]
	90	108.68 (1.55) [a]	104.10 (1.58) [b]	116.65 (2.04) [a,b]
Biodegradable Material				
3.18	50	96.23 (0.39)	98.06 (0.16)	91.07 (0.87)
	90	99.23 (12.10) [a]	102.07 (0.76) [a]	95.56 (0.49)
6.35	50	96.88 (0.49)	93.82 (1.91)	89.11 (3.56)
	90	102.43 (2.17) [a]	99.88 (1.94) [a,b]	98.45 (3.89) [b]

* Value in parentheses indicates the sample standard deviation where *n*=6.
[a,b] Means in a row with a common superscript letter differ ($P < 0.05$), as analyzed by one-way ANOVA, indicates effect of moisture content.

Table 3.5: Effects of experimental variables on percent average relaxation, PAR (%).

Grind Size (mm)	Temperature (°C)	Moisture Content (% w.b.)		
		8	12	16
Refuse Derived Fuel Fluff				
3.18	50	31.41 (1.15) * [a]	35.46 (0.71) [b]	31.86 (5.15) [a,b]
	90	28.00 (0.52) [a]	31.90 (1.20) [b]	21.65 (1.18) [a,b]
6.35	50	31.53 (0.38) [a]	32.23 (2.65) [a,b]	31.17 (4.84) [b]
	90	27.44 (0.76) [a]	29.43 (0.39) [b]	22.62 (1.07) [a,b]
Biodegradable Material				
3.18	50	33.47 (0.28)	32.02 (0.19)	36.52 (0.71)
	90	34.58 (1.16) [a,b]	29.11 (0.51) [a]	33.40 (0.39) [b]
6.35	50	32.29 (1.44)	34.71 (1.30) [a]	37.68 (1.78) [a]
	90	29.16 (1.07) [a]	30.25 (1.34) [a,b]	31.52 (2.16) [b]

* Value in parentheses indicates the sample standard deviation where *n*=6.
[a,b] Means in a row with a common superscript letter differ ($P < 0.05$), as analyzed by one-way ANOVA, indicates effect of moisture content.

3.5 Conclusions

A characterization study of the thermochemical and biochemical properties of MSW RDF-fluff was conducted, yielding the following conclusions:

1. Ash content of all samples remains well above the 1% by mass required to be considered a first quality fuel pellet; this is likely due to the ‘dustiness’ of the material and consistent with past examination of RDF pellets.
2. Proximate analysis verified that RDF has a high organic content, in which carbon accounts for approximately 40% of each of the pellet samples by mass.
3. The higher heating value (HHV) was determined to be 14 – 16 MJ/kg for all samples using the Freidl et al. model and verified using experimental gross energy measurements for the two biodegradable material pellet samples.
4. Very low glucose and non-existent xylose content of the biodegradable material samples conclude that biochemical conversion processes are not suitable for MSW RDF-fluff.

The compression and relaxation characteristics of RDF-fluff samples were investigated and the following conclusions were made:

1. The compact density of RDF pellets was only affected by grind size; density was highest when pellets produced from material that was ground with a 6.35 mm screen in the knife mill; compact density of biodegradable pellets increased with increasing pelleting load and temperature, while there was no significant effect of moisture content or grind size of the material.
2. Both Walker’s and Jones’ model resulted in good fits to the experimental data and indicated that the biodegradable material had a higher compressibility than the RDF material for all conditions.
3. Fitting of the Kawakita-Lüdde model to the compression data resulted in good fit but no correlation found between the model parameters and the experimental variables.

4. The Cooper-Eaton model indicates that the primary mechanism in the densification of RDF derived biomass is attributed to particle rearrangement, with some secondary influence from plastic deformation or particle fragmentation.
5. Peleg and Moreyra's model, fit to the data, estimated the asymptotic modulus (E_a) for each sample and indicated that pellets formed from the RDF material had a higher E_a value than the biodegradable pellets; RDF-derived materials are determined to have comparable E_a values to literature values for other biological residues.

Chapter 4

4 Pelletization of Refuse-Derived Fuel Fluff to Produce High Quality Feedstock

A version of this chapter has been submitted for presentation at the 2017 CSBE technical conference:

- Sprenger, C., L.G. Tabil, M. Soleimani, J. Agnew, and A. Harrison. 2017. Pelletization of refuse-derived fuel fluff to produce high quality feedstock, presented at the *CSBE/SCGAB 2017 Annual Conference, Winnipeg, MB, August 6-10*. CSBE Paper No. 17-147.

4.1 Contribution of the MSc Candidate

The MSc candidate conducted literature review, planned and executed the characterization and pelleting experiments, acted as the client for the feasibility study, and prepared the manuscript for this report on producing high quality pellets from refuse-derived fuel fluff. Her research supervisor, Lope G. Tabil, provided guidance during planning of experiments and editorial advice during manuscript preparation. A researcher in the Chemical and Biological Engineering Department, Majid Soleimani provided guidance during planning of her experiments and assisted in setting up and running some of the pelleting procedures. Joy Agnew and Amie Harrison at the Prairie Agricultural Machinery Institute, Humboldt, SK, were consulted regarding the techno-economic feasibility study and provided an extensive report for the MSc candidate to summarize and analyze.

4.2 Abstract

Due to its primarily organic composition municipal solid waste (MSW) is a suitable feedstock for thermochemical conversion. Current technologies process the MSW into refuse-derived fuel (RDF) fluff before conversion. Bench and pilot-scale densification trials were conducted to determine the parameters

required to produce a higher quality feedstock from the MSW RDF material in a pellet form. Characterization MSW-RDF fluff sample showed that the composition of the material was approximately 35% paper, 22% plastics, 14% fabrics, 6% organics/wood, and 23% fines by weight. The RDF was densified, as well as the biodegradable (paper and wood) fraction of the RDF stream to compare quality of pellets for the two material compositions. A single pelleting trial was conducted to examine the compaction parameters that would produce high quality pellets: sample material, grind size, moisture content, temperature and pelleting pressure. It was determined that quality pellets, for both materials, were formed at a grind size of 6.35 mm at 16% moisture under pelleting conditions of 90°C and 4000 N applied load. Pilot-scale pelleting was then completed to emulate industrial pelleting process utilizing the parameters from the single pelleting operation that were deemed to produce quality pellets. All of the samples produced durable pellets (88-94%), with the ash content around 20% for all samples. A techno-economic feasibility study determined that 6.35 mm diameter pellets could be produced at a large scale for an average cost of $38/Mg, which includes both size reduction and densification processes, although the aggressive process of the size reduction required indicates that it may not be a technically feasible option.

4.3 Introduction

There is potential for the utilization of municipal solid waste (MSW) as an advanced biofuels feedstock suitable for thermochemical conversion processes in the form of refuse derived fuel (RDF). This application would enable diversion of waste from landfill operations, the traditional destination for single-stream waste. A state-of-the art project at the Edmonton Waste Management Centre (Edmonton, AB) sees the production of methanol from MSW RDF through low-severity gasification technology in a collaboration with Enerkem Alberta Biofuels (Enerkem Alberta Biofuels 2015). Municipal solid waste (MSW) is a very heterogeneous waste product and its composition and properties vary by source location and season. The primary organic components are plastics, paper, textiles, and food/wood waste, combined with inorganic metals, glass, and various composites. The current feedstock is in the form of a 50.8 mm (2-inch) fluff, however, densification of this material would produce a higher quality feedstock that is more durable, easier to handle, and more uniform. A first quality fuel pellet must contain less than 1% by weight ash and have a calorific value greater than 18.6 GJ/t of fuel (www.evergreenbioenergy.com). Municipal solid waste RDF has a higher ash content, approximately 10-22% (NETL 2015); in addition, the inorganic elements of the waste feedstock create challenges in the conversion processes including slagging and loss of efficiencies. Improving these characteristics would also increase the potential of RDF as a quality fuel feedstock (RAEFS 2011).

Single-pelleting experiments allow investigation of the effects of different variables known to influence biomass densification; and thus, determine the parameters that produce high quality pellets. Process conditions such as applied pressure, die geometry and temperature, and hold-time are variables that can be altered to improve the quality of pellets, while moisture content, particle size distribution, and biochemical composition are also influential as variations of material properties. Increasing the applied pressure during the densification process results in higher density pellets, while a level at which plastic deformation occurs is necessary for improved strength and durability (Yaman et al. 2000). A hold-time at maximum load also reduces the effect of 'spring-back' due to elastic deformation. As the operating temperature during densification is increased, the material's resistance to applied load is reduced and the degree of compaction is improved. The die geometry has an impact on pelleting as it indicates the required pressure required to compact the material and overcome the friction of the inner die surface; smaller diameters also increase the power required to produce a pellet due to the increased restriction to material flow. Moisture contents between 8-12% wet basis (w.b.) in cellulosic materials have been shown to produce denser pellets, as water acts as a binder, increasing the contact area available for the formation of van der Waal's forces (Mani et al. 2003). Particle size distribution influences the extent of compaction from particle rearrangement (Adapa et al. 2013). Traditional, lignocellulosic biomass feedstocks are very resistant to deformation, thus the biochemical composition of the material is influential on the need for any pretreatment steps. The plastic fraction present in MSW provides a variable whose effect on the quality of pellets is currently unknown.

The effects of each of these characteristics assist in determining the requirements for effectively and efficiently producing higher quality pellets.

Briquetting (larger sized product than pellets) of municipal waste has been implemented in numerous regions around the world in order to utilize the biomass as a solid fuel since it has a higher energy density and is easier to handle than raw MSW (Shrestha and Singh 2011). Most of the process development has been driven by the waste-to-energy industry, however briquetting has long been used to make other biomass based-fuel products (Krizan et al. 2011). There has been research conducted on the composition and thermochemical properties of MSW in order to justify its use as an energy feedstock (Gidarakos et al. 2005). However, there is little research available regarding the optimization process for densifying MSW-derived materials in order to efficiently produce quality briquettes or pellets. These types of studies have been conducted for other biomass such as straws, alfalfa, and wood chips, and are important as each material behaves differently when densified and has its own unique set of material and process variables required to produce a quality densified product (Tabil and Sokhansanj 1996b). As such, it is critical to establish experimentally determined parameters that are most suitable for producing a quality densified refuse derived fuel product from MSW.

The objective of this study is to determine the factors in the processing of high quality MSW-RDF pellets and to investigate the feasibility of implementing the production of such pellets in a full-scale operation. This was completed by characterization of the raw RDF-fluff feedstock, followed by pelleting trials, both single and pilot-scale, to determine the effect of pelleting parameters on pellet quality, concluded by a techno-economic feasibility study. This chapter focuses on the stages of scale-up for pelleting MSW-RDF, in comparison to the previous chapter which focused on the thermochemical and compression/relaxation characteristics of the biomass from data that was collected during the pelleting process outlined here.

4.4 Material and Methods

4.4.1 Materials

Municipal solid waste (MSW) refuse-derived fuel (RDF) fluff was supplied by the Edmonton Waste Management Centre (EWMC), Edmonton, AB, Canada in July 2015. The fluff upon receipt had a moisture content of 5.5% wet basis (w.b.) and an average bulk density of 54.6 kg/m^3. It is to be noted that the EWMC facility experiences RDF-fluff moisture contents of upwards of 20-30% w.b; discussion on this variation is discussed in subsequent sections.

Pelleting characteristics were examined for two different fractions of the RDF-fluff material. The first material utilized the RDF in its raw composition; this consisted of approximately 35% paper, 22% plastics, 14% textiles, 6% wood/organics, and the remainder fines and inerts, determined by a composition sort. The second material consisted of only biodegradable components, wood and paper, after undergoing sorting to remove plastics and textiles.

Each material was ground using two screen sizes, 3.18 mm and 6.35 mm, of the knife mill (Retsch GmbH, Haan, West-Germany). The moisture content of each of the 4 material/grind size samples was determined according to ASABE Standard S358.3 (ASABE 2012), then adjusted to 8%, 12%, and 16%, w.b. Samples were allowed to equilibrate in air-tight containers for a minimum of 3 days prior to the start of the experiment.

4.4.2 Characterization of MSW RDF-Fluff

Knowledge of the properties of raw RDF-fluff is required to analyze the results of the densification experiments as to the improvement to overall feedstock quality.

4.4.2.1 Physical Properties

Moisture content of the MSW-RDF fluff material upon receipt was measured. Approximately 5 g of the original sample was placed in an oven at 105°C overnight. The change in mass was recorded and the wet basis moisture content was calculated. Three replicates were made to determine the average moisture. Ash content was then determined by subjecting the dried samples to incineration in a furnace at 575 ± 25°C for 24 ± 6 h. Crucibles containing the ash sample were then placed in a desiccator to cool. Weight measurements were recorded for the empty crucible and for the crucible containing the sample before drying, before incineration, and after incineration. Percent ash was calculated from the change in mass from the dried sample.

The bulk density of the received MSW-RDF fluff sample was measured using a 5850 mL (cm^3) container. Six replicates were completed to account for the heterogeneity of the material.

Particle size analysis for the received MSW-RDF fluff sample was completed following a variation on the withdrawn ASTM test standard E828-81 (ASTM 1997) from sieving analysis. Deviation from the test method was due to restrictions in testing equipment. A sieve shaker with large rectangular pans (less than 0.5 m^2) was used to analyze four replicates of approximately 500 g samples of RDF fluff. The sieve sizes in the shaker are 50.8 mm, 19.1 mm, 12.7 mm, 6.35 mm, 4.76 mm, and 1.41 mm. The shaker was run for 10 min. The mass of the material retained on each sieve was measured and recorded. Four replicates were completed for this analysis.

4.4.2.2 Material Composition

Composition of the MSW-RDF fluff was determined by hand sorting using the categories used by the Edmonton Waste Management Centre: paper, film plastic, rigid plastic, fabric, metal, glass/ceramic and organics. An extra category for fines and indeterminables was added to account for the fraction of the material that could not be evaluated as to its composition. Three sorting sessions were completed with sample sizes of approximately 1.5 kg.

4.4.3 Sample Preparation

Densification trials were conducted to compare the pelleting outcomes for the raw RDF-fluff material as well as a sorted fraction in which only the biodegradable material (paper and wood) was included.

4.4.3.1 Particle Size Reduction

Each of the samples were ground using a knife mill (Retsch GmbH, Haan, West-Germany). Originally a hammer mill was to be used for the size reduction as this is a machine commonly used for biomass samples due to its high throughput, however, the plastic films in the sample would stretch through the screen rather than being reduced to the desired particle size. Therefore, in order to obtain a uniform sample for the densification experiments, it was decided that a knife mill would provide the necessary size reduction. The screen sizes used for grinding were 6.35 mm and 3.18 mm.

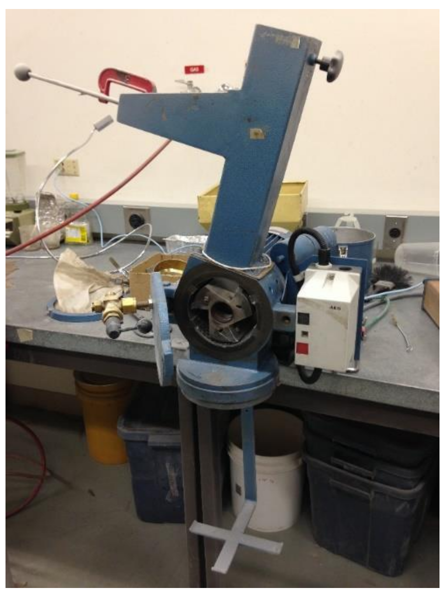

Figure 4.1: Retsch knife mill used to grind samples.

ASAE standard S319.3 (ASAE 2008) was followed to analyze the particle size distribution of each ground sample. Three replicates of 100 g samples for each material and grind size was agitated using a large rectangular screen separator for 10 min.

The particle density for each sample (grind size and moisture content combinations) was determined using a gas pycnometer (Multipycnometer, Quantachrome Corp., Boynton Beach, FL), in which the true volume is measured, accounting for the porosity of the sample. Nitrogen was used as the fluid in the closed system.

4.4.3.2 Sample Conditioning

For the single pelleting experiment, the moisture content of the material was adjusted to three levels to examine the effect on pellet quality. The moisture content at storage conditions was first determined for each sample. The initial mass of each sample (approximately 3 g) was recorded and then the samples were placed in a vacuum oven at 105°C RDF overnight (24 h), according to ASABE standard, ASAE S358.2 (ASABE, 2012). The difference in mass was measured and moisture content was expressed in wet basis. RDF and biodegradable materials were adjusted to 8, 12, and 16% w.b., by mixing in the necessary amount of distilled water to the material to achieve a 50 g sample and allowing the sample to come to equilibrium inside of a sealed container for a minimum of 48 h at room temperature.

Samples for the pilot-scale experiments were prepared in the same manner, although the samples were 4 kg and rested for a minimum of 72 h once water was added in sealed, large plastic bags at room temperature to reach equilibrium before pelleting.

4.4.4 Single Pelleting Trials

The purpose of completing a single pelleting experiment is to examine and analyze the compaction characteristics of densification of the different materials and to determine the effect of several factors on the production of quality pellets.

4.4.4.1 Experimental Design

A four factor factorial design created using Design Expert 9 (Stat-Ease, Minneapolis, MN) was used to evaluate the effect of pelleting parameters on RDF and biodegradable samples. Grind size was compared at two levels: 3.18 and 6.35 mm; these values were chosen as they are common grind sizes used in industry and are suitable for producing 6.35 mm diameter pellets. Moisture content (m.c.) was compared at three levels: 8, 12, and 16% w.b.; these values were chosen based on literature m.c. ranges of 7-12% for similar biomass pelletization trials, however 16% was chosen to represent he high moistures that are experienced in Edmonton. The pellet die temperature was compared at two levels: 50 and 90°C; these temperatures are representative of those achievable with the pilot-scale equipment. Pelleting pressure was compared at three levels: corresponding to compressive forces of 2, 3, and 4 kN. This resulted in 36 treatment combinations for each of the RDF and biodegradable materials. Twelve pellets were produced for each treatment combination.

4.4.4.2 Single Pelleting Unit (SPU) Procedure and Apparatus

A single pelleting experiment was first completed to evaluate the compaction and compression characteristics of densifying RDF type material, and to determine the most suitable process parameters to do so. Each sample was densified using a single pelleting unit (SPU) mounted on an Instron testing machine (Model No.3366, Instron Corp., Norwood, MA) to apply the appropriate load. This SPU consists of a cylindrical die with the plunger attached to the moving crosshead of the Instron machine as seen in Figure 2. A heating element is attached to the pelleting die in order to control the temperature of the process; the experiment involved comparing the effect of pelleting temperature at values of 50°C and 90°C. Approximately 0.55 ± 0.05 g of biomass was fed into the die to produce each pellet. The Instron was then used to apply the desired force (2, 3, and 4 kN) to compress the charged material at a rate of 50 mm/min, at which point the plunger was held for 60 s as a retention time to avoid "spring-back" typical of densified biomass. A gate in the platform of the SPU was then opened manually to allow the plunger to eject the newly formed pellet from the die. The same software that was programmed to complete the densification process also recorded the time and force-displacement data for each pellet. Twelve pellets (replicates) were produced for each treatment combination; they were stored at room conditions for analysis after a period of relaxation.

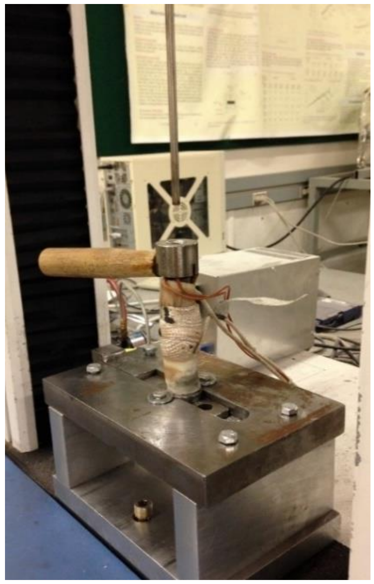

Figure 4.2: Single pelleting unit mounted on an Instron Model No.3366 tester for pelleting of samples.

4.4.4.3 Pellet Density and Dimensional Stability

Pellet mass and dimensions (length and diameter) were measured immediately following densification and again after 14 d relaxation in storage. From this, density was calculated to evaluate the change in density of the biomass. Changes in volume immediately following densification (V_o) and after 14 d relaxation (V_{14}) were used to evaluate the volumetric stability of each pellet.

$$Volumetric\ Stability = \frac{V_0 - V_{14}}{V_0} 100\% \tag{4.1}$$

4.4.4.4 Moisture Content

Moisture content was determined immediately after pelleting and after the 14 d relaxation period to determine the extent of the change in moisture during pelleting and storage. In each case, the initial mass of 2-3 pellets was measured before they were dried at 105°C overnight in a forced-air oven for 24 h, or until there was no change in moisture over a 1 h period. The final mass of the pellets was measured and the wet basis (w.b.) moisture content was determined.

4.4.4.5 Tensile Strength

Tensile strength of the pellets was measured using the diametral compression test, adapted from the pharmaceuticals industry to evaluate the strength of biomass pellets (Tabil and Sokhansanj 1996a). Pellets were cut into approximately 2 mm tablets using a table laser cutter to provide greater consistency in cutting. The diameter and thickness of each tablet were recorded prior to being tested. Tablets were individually placed on their edge on the lower padded (a layer of card stock) plate (Figure 4.3). The Instron machine was fit with a padded (card stock) upper plunger with a flat face which was used to apply a force to the tablet with a 1000 N load cell at a rate of 1 mm/min until failure. Failure resulting in specimens cracking or breaking in two halves along the loading axis were accepted, with all other failure types being discarded. Applied force was recorded by the Instron software, and the maximum load at failure was used to calculate the tensile strength for the tablet using equation 4.2, where σ_x is the tensile strength (MPa), F is the load at fracture (N), d is the diameter of the tablet (mm) and l is the thickness of the tablet (mm) (Iroba et al. 2014). Twenty-eight replicates (tablets) from 6 pellets were made for each treatment sample to account for variation in the heterogeneous nature of the pellets.

$$Tensile\ Strength\ (\sigma_x) = \frac{2F}{\pi dl} \tag{4.2}$$

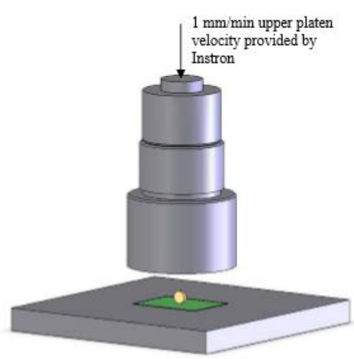

Figure 4.3: Diametral compression apparatus fitted to the Instron machine with tablet loaded on its edge (Shaw, 2008).

4.4.5 Pilot-scale Pelleting Trial

Following evaluation of sample pellets prepared with the SPU, a pilot-scale experiment was conducted to emulate an industrial pelleting process. The parameters from the SPU experiment that yielded the best quality pellets (see Section 4.5.3.5) were implemented as the treatment combinations for this experiment. Samples ended up consisting of 6.35 mm grind, 16% w.b. moisture RDF produced with either no added heat, or preheated material using the conditioning chamber of the pellet mill. The other sample was 6.35 mm grind, 16% w.b. moisture biodegradables produced with preheated material. A fuel additive known as AK-2 was added as a factor for the pilot-scale experiment. AK-2 (US Patent No. 7,785,379 B2; August 31, 2010) is used as an additive that helps to raise the fusion point of inorganic elements in the sample and to reduce volatile emissions (Emami et al. 2014). This was either added at 0.15% by mass or omitted for each of the above samples prior to pelleting; therefore, there was a total of 6 treatment combinations. Each sample consisted of 4 kg of prepared material.

Figure 4.4: CPM-CL5 pilot-scale pelleting unit used for pelletizing samples.

4.4.5.1 Unit and Bulk Density

Length, diameter, and mass of pellets were measured to calculate the unit density of the pellets produced by the pilot-scale pellet mill. Twenty replicates were completed for each sample.

Bulk density was determined according to the standard: ASABE S269.4 (ASABE 2012). A 0.5 L cylindrical container was filled with pellets from a funnel and the container was levelled off. The mass of the sample was measured to calculate the density.

4.4.5.2 Durability

Durability of pellets formed from the pilot-scale pellet mill was determined according to ASABE standard ASAE S269.4 (ASABE 2012). The device used was an air-tight tumbler specified in the standard method. A 50 g test sample was first screened with a No. 3½ sieve (5.7 mm opening) to screen to remove any fines. It was then tumbled for 10 min at 50 rpm in the machine. The pellets were screened again using the same sieve after tumbling and the material retained was weighed to determine the durability (%) according to equation 4.3.

$$Durability = \frac{mass\ of\ pellets\ after\ tumbling}{mass\ of\ pellets\ before\ tumbling} * 100 \tag{4.3}$$

4.4.6 Feasibility Study

The final investigation into the production of high quality pellets using MSW RDF-fluff as a feedstock was a techno-economic feasibility study for a full-scale up utilizing the pelleting characteristics determined in single and pilot-scale trials. The complete study was completed by PAMI, and a final report was generated for analysis and discussion in this project.

The aim was to determine the cost associated with scaling up the process of MSW RDF-fluff densification (Agnew and Harrison 2017). The study was conducted specifically for the context of the Edmonton Waste

Management Centre, in terms of existing infrastructure and throughput. The contracted 140,000 Mg/yr of MSW RDF-fluff produced by the EWMC for Enerkem represents the throughput required by the system.

Equipment for both the size reduction and pelletization processes were included in the report to determine the technical feasibility of both processes based on available technologies. Economic feasibility of the scale-up operation was determined by calculating the capital and operating costs associated with the production of MSW RDF pellets on a per tonne basis.

4.5 Results and Discussion

4.5.1 Characterization of MSW RDF-fluff

The MSW-RDF fluff received from Edmonton was characterized to determine the original properties of the waste before processing; this included bulk density, moisture content, composition, and particle size distribution.

4.5.1.1 Physical Properties

MSW-RDF fluff samples had an average moisture content of 5.5% w.b. as received. This appears to be a relatively low moisture content relative to the values that were presented in correspondence with the Edmonton Waste Management Centre; it was noted that moistures up to 20-30% had been measured at the site, particularly in warmer months where yard wastes were more prevalent. Ash content of the received sample was determined to be 28.3% (dry matter basis). Values above 20% for MSW were expected, however the larger value could be attributed to the observation that the sample provided was very dirty, indicating a high proportion of inorganic dirt which would raise the ash content. The average bulk density of the raw material was measured to be 54.63 kg/m^3.

Particle size analysis was conducted for five replicates of the RDF fluff. Over 40% of the material measured between 1.91-5.08 cm; no material was retained on the 50.8 mm (2 in) sieve, this is consistent with the fact that the RDF material was prepared using a 2-inch disc shredder. A complete distribution is listed in B.1 of the Appendix.

4.5.1.2 Material Composition

Three sorts were completed for the RDF fluff material that was provided.

Table 4.1 compares the average composition that was provided by the Edmonton Waste Management Centre and the average composition from the manual-sorts that were completed in the lab. It can be reiterated that a category for material that was indeterminable during the sort was created as fines; this material was predominantly less than ¼” in size. All of the other categories are very similar excluding the organics (which could be accounted for in the fines category of the sort), indicating that this MSW-RDF fluff material that was provided is a representative sample of the average Edmonton RDF composition.

Table 4.1: Municipal solid waste refuse-derived fuel fluff composition comparing the results of the hand sorting in the lab and the averages provided by the Edmonton Waste Management Centre (EWMC).

Material	Sort Average (%)	EWMC Average (%)
Paper	35.6 (1.1)	36.6
Film Plastic	12.7 (0.7)	18.4
Rigid Plastic	9.3 (0.9)	12.8
Fabric	13.5 (1.7)	16.8
Metal	0.3 (0.0)	2.5
Glass/Ceramic	0.0 (0.0)	0.0
Organics/Wood	5.6 (0.3)	12.9
Fines	23.1 (2.0)	n/a

* Value in parentheses is standard deviation, n=3.

4.5.2 Physical Properties of Prepared Samples

4.5.2.1 Particle Size

The following images are examples of the ground material.

Figure 4.1: Example of RDF-fluff before (left) and after (right) particle size reduction using a knife mill fitted with a 6.35 mm screen.

Each material grind size was evaluated by sieve analysis to determine the particle size distribution (Appendix: Table B.2). The geometric mean diameter, d_{gw}, of RDF material produced using a 3.18 mm and 6.35 mm screen was 0.67 mm and 0.95 mm, respectively; similarly, the d_{gw} of the biodegradable material was 0.50 mm and 1.19 mm, respectively. It can be noted that for each sample, the geometric mean diameter of the particles for the sample is much lower than the grind size; this can be attributed to the heterogeneity of the materials and to the high quantity of fines in the raw sample (Table 4.1

Table 4.1). In each case, the majority of the sample (by mass) appears to be retained within 4 sieve sizes below the maximum expected from the screen size used. In the 3.18 mm samples, there appears to be material that is larger than the screen size; this could be attributed to the spring-back of particles after grinding, and or agglomeration of material into clumps.

4.5.2.2 Particle Density

Particle densities were experimentally determined using the gas pycnometer (Table 4.2

Table 4.2). These densities represent the maximum compact density that can be achieved by particle rearrangement alone. The RDF material has a lower average particle density than the biodegradable material, which can be attributed to the presence of less dense film plastics.

Table 4.2: Particle density (kg/m^3) of each sample material prepared for single pelleting trial.

Moisture Content	RDF Material	Biodegradable Material

(% w.b.)	3.18 mm	6.35 mm	3.18 mm	6.35 mm
8	1248 (12)*	1166 (48)	1366 (28)	1279 (6)
12	1221 (45)	1171 (47)	1358 (3)	1292 (78)
16	1235 (22)	1096 (45)	1343 (50)	1279 (47)

*Value in parentheses is standard deviation, n=3.

4.5.3 Factors Affecting Pellet Quality Using Single Pelleting Trial

Single pelleting unit trials helped to evaluate the compression and compaction characteristics of the different materials under a variety of pelleting conditions.

4.5.3.1 Pellet Density

Density of each material was significantly increased by pelletization; considering the bulk density of the RDF-fluff was 54.6 kg/m^3. The biodegradable material alone achieved the greatest increase in unit density; this can likely be attributed to the fibrous nature of the papers and wood acting as mechanical, inter-locking binders. In the RDF and plastic samples, the densification was still significant, however the hydrophobicity and elastic properties of the film plastics caused some spring-back and relaxation, hence the lower density than the biodegradables. A study by Krizan et al. (2011) was able to produce briquettes from mixed municipal waste with compact densities of up to 900 kg/m^3; the composition of the raw material was similar to the RDF used in this experiments, with the addition of up to 38% woodchips. There is no literature documenting achieved compact density for pellets made from MSW.

Certain experimental factors also played a role on the density of the pelletized product. For the RDF material, it was found that moisture content, pressure, and grind size had a significant influence on the density of the formed pellets. The 6.35 mm samples had greater density than the 3.18 mm samples.

Table 4.3: The effect of pelleting parameters on compact density (kg/m^3) of RDF and biodegradable material pellets.

Grind Size (mm)	Moisture Content (% w.b.)	Applied Load (kN) 2		3		4	
		Die Temperature (°C)					
		50	90	50	90	50	90
Refuse Derived Fuel Fluff							
3.18	8	938 (34)*	885 (28)	887 (32)	887 (34)	918 (47)	926 (37)
	12	898 (40)	870 (33)	896 (20)	913 (17)	937 (24)	929 (19)
	16	905 (20)	923 (40)	915 (23)	938 (19)	926 (13)	930 (45)
6.35	8	950 (36)	972 (36)	993 (47)	1000 (41)	1010 (29)	1010 (48)
	12	988 (44)	979 (40)	989 (49)	998 (42)	1007 (58)	990 (35)
	16	982 (36)	1014 (40)	991 (39)	1018 (34)	993 (59)	1010 (28)
Biodegradable material							
3.18	8	1126 (15)	1134 (21)	1194 (27)	1218 (18)	1206 (28)	1237 (22)
	12	1179 (19)	1190 (19)	1199 (12)	1232 (24)	1235 (22)	1250 (34)
	16	1154 (15)	1175 (13)	1194 (29)	1217 (16)	1219 (17)	1254 (29)
6.35	8	1122 (15)	1155 (38)	1181 (27)	1199 (14)	1253 (25)	1285 (18)
	12	1135 (25)	1184 (33)	1189 (29)	1227 (19)	1233 (23)	1255 (14)
	16	1161 (30)	1182 (20)	1204 (36)	1217 (21)	1227 (18)	1242 (21)

*Value in parentheses indicates the sample standard deviation where n=12.

For the biodegradable materials, increasing the temperature, pressure, and moisture content of the pellet die and plunger had a positive correlation on increasing density. There was however, no significant effect of grind size of the material. While no literature is available for the effect of pelleting and material parameters on the compact density of MSW, a study on the pelleting of alfalfa found that screen size used for grinding, has less effect on the quality of a pellet than the geometric mean diameter which can vary greatly for the same grind size (Tabil and Sokhansanj 1996b).

The Design Expert software also determined that there are other multiple factor interactions between pelleting parameters that are significant in terms of compact density. Table 4.4 summarizes the analysis of variance (ANOVA) for all design interactions; values of “p-value” less than 0.05 indicate a significant interaction at a 95% confidence level. It is important to note that there is a three-factor interaction between moisture content, grind size, and pressure, however, it does not indicate whether each factor has a positive correlation on compact density at the same time.

Table 4.4: Significance of multiple factor interactions on compact density determined by analysis of variance (ANOVA) in Design Expert.

Interaction		p-Value	
Levels	Factors	RDF Material	Biodegradable Material
1FI [a]	Moisture Content	0.0036	<0.0001
	Temperature	0.1022	<0.0001
	Pressure	<0.0001	<0.0001
	Grind Size	<0.0001	0.5743
2FI	Moisture Content x Temperature	0.0093	0.4270
	Moisture Content x Pressure	0.1363	<0.0001
	Moisture Content x Grind Size	0.8520	0.0010
	Temperature x Pressure	0.1287	0.8247
	Temperature x Grind Size	0.1264	0.5890
	Pressure x Grind Size	0.1092	0.0023
3FI	Moisture Content x Temperature x Pressure	0.2788	0.1179
	Moisture Content x Temperature x Grind Size	0.4604	0.1170
	Moisture Content x Pressure x Grind Size	0.0149	0.0002
	Temperature x Pressure x Grind Size	0.0863	0.0244
4FI	Moisture Content x Temperature x Pressure x Grind Size	0.2201	0.8103

[a] 1FI means one-factor interaction, indicates the number of factors in the statistical analysis

4.5.3.2 Dimensional Stability

Dimensions of the pellets were measured at Day 0 immediately after pelleting and on Day 14 after 2 weeks of relaxation to determine the dimensional stability of the pellets. For this experiment, the stability was represented as volumetric stability (equation 4.1).

Negative results indicate volumetric expansion, while positive values represent volumetric contraction during the relaxation period. Biodegradable pellets show very little change in volume, except for at moisture contents of 16% for the larger grind size; this could be a result of evaporation of the residual moisture from the pellets during relaxation, but may require further investigation. Mani et al. (2004) found that corn stover briquettes expand more with increased moisture content.

In most of the experimental combinations, the RDF pellets experienced volumetric expansion after the 2-week relaxation period. This is primarily due to the hydrophobicity and elasticity of the plastic fraction in the sample; moisture in the sample meant that the pellet did not hold its shape as well. Further, the plastics did not melt during pelleting therefore they resisted deformation.

Pellets produced from material prepared with a larger grind size, 6.35 mm, appeared to have a greater volumetric stability that those from a smaller grind size. This may be attributed to larger particles melting from the higher temperatures and sealing in the remaining material.

Table 4.5: Effect of pelleting parameters on dimensional (volumetric) stability (%) of refuse-derived fuel fluff and biodegradable pellets.

Grind Size (mm)	Moisture Content (% w.b.)	Applied Load (kN) 2		3		4	
		Die Temperature (°C)					
		50	90	50	90	50	90
Refuse Derived Fuel Fluff							
3.18	8	-9.36 (4.16)*	0.28 (2.62)	-1.20 (4.66)	-6.63 (3.13)	-6.72 (3.03)	-1.41 (4.46)
	12	-9.85 (3.90)	-0.43 (2.74)	-2.61 (2.91)	-6.48 (6.36)	-7.05 (5.79)	-0.50 (2.66)
	16	-5.94 (1.76)	-2.81 (2.65)	-1.59 (1.89)	-6.86 (3.17)	-9.45 (3.79)	0.15 (3.30)
6.35	8	-5.68 (3.12)	-2.42 (3.12)	-2.10 (4.01)	-5.11 (4.16)	-8.38 (2.69)	-2.67 (4.09)
	12	-9.35 (3.48)	-2.16 (4.46)	-4.11 (3.79)	-10.70 (4.62)	-6.52 (4.90)	-1.82 (3.14)
	16	-3.24 (4.75)	5.31 (5.16)	1.07 (6.29)	0.83 (5.56)	-0.50 (4.78)	8.30 (3.10)
Biodegradable material							
3.18	8	-0.39 (1.59)	-0.55 (1.82)	1.42 (2.01)	-0.55 (1.82)	2.20 (3.41)	0.80 (1.65)
	12	-1.22 (1.55)	1.02 (2.06)	-0.48 (2.65)	1.02 (2.06)	0.95 (1.68)	0.73 (2.93)
	16	-0.56 (1.11)	0.56 (2.15)	1.52 (2.47)	0.56 (2.15)	0.57 (1.84)	1.91 (1.39)
6.35	8	-1.16 (3.59)	1.75 (1.43)	-0.77 (1.02)	1.75 (1.43)	-5.89 (1.74)	-4.23 (2.10)
	12	-0.99 (2.48)	1.40 (1.23)	-0.41 (1.95)	1.40 (1.23)	-1.65 (3.81)	1.34 (2.49)
	16	7.72 (3.04)	8.90 (2.06)	9.57 (1.56)	8.90 (2.06)	7.29 (1.85)	9.05 (1.71)

*Values in parentheses indicate the sample standard deviation where n=9.

Similar biomass pelleting research by Shaw (2008) indicated slightly lower pellet densities after relaxation due to expansion for poplar and wheat straw, similar to expansions seen by the RDF pellets. The biodegradable material reacted similarly to pretreated material in the same experiment, wherein some contraction was seen opposed to expansion, indicating higher dimensional stability. It is possible that the broad range of physical and chemical origins, uses, and disposal methods of the various components of the MSW material act as pretreatment methods often required for densification of biomass.

4.5.3.3 Moisture Content

The pelleting process and relaxation period both resulted in decreases in moisture content in the pellets. Pelleting resulted in a 1-10 % decrease in moisture content depending on the initial moisture content and the temperature of the pelleting die. Storage resulted in a further 1-3% decrease in moisture content of the pellets.

4.5.3.4 Tensile Strength

Tensile strength of the pellets was derived from the maximum load at failure under diametral compression. The following table summarizes the average tensile strength for pellets produced under each treatment combination.

Table 4.6: Effect of experimental factors on the tensile strength (MPa) of refuse-derived fuel fluff and biodegradable material pellets.

Grind Size (mm)	Moisture Content (% w.b.)	Applied Load (kN) 2		3		4	
		Die Temperature (°C) 50	90	50	90	50	90
Refuse Derived Fuel Fluff							
3.18	8	0.142 (0.067)*	0.166 (0.074)	0.165 (0.070)	0.112 (0.048)	0.102 (0.042)	0.206 (0.087)
	12	0.121 (0.102)	0.247 (0.089)	0.176 (0.075)	0.175 (0.094)	0.142 (0.061)	0.324 (0.098)
	16	0.255 (0.088)	0.323 (0.113)	0.285 (0.111)	0.284 (0.125)	0.258 (0.085)	0.361 (0.124)
6.35	8	0.271 (0.142)	0.460 (0.321)	0.334 (0.305)	0.337 (0.182)	0.310 (0.169)	0.275 (0.185)
	12	0.491 (0.319)	0.491 (0.245)	0.532 (0.345)	0.411 (0.298)	0.386 (0.243)	0.474 (0.244)
	16	0.450 (0.206)	0.667 (0.348)	0.630 (0.246)	0.430 (0.180)	0.420 (0.215)	0.533 (0.264)
Biodegradable material							
3.18	8	0.406 (0.128)	1.072 (0.333)	0.733 (0.197)	0.858 (0.272)	0.588 (0.157)	1.369 (0.284)
	12	0.772 (0.200)	1.264 (0.314)	0.715 (0.214)	0.988 (0.251)	0.838 (0.261)	1.360 (0.329)
	16	0.984 (0.240)	1.267 (0.252)	1.296 (0.532)	1.086 (0.223)	0.967 (0.259)	1.389 (0.312)
6.35	8	0.724 (0.302)	1.429 (0.441)	0.897 (0.290)	0.993 (0.361)	0.993 (0.353)	1.423 (0.454)
	12	0.853 (0.332)	1.473 (0.503)	1.227 (0.466)	1.477 (0.404)	1.004 (0.349)	1.823 (0.716)
	16	1.155 (0.246)	1.953 (0.562)	1.822 (0.675)	1.733 (0.482)	1.519 (0.515)	2.117 (0.651)

*Values in parentheses indicate the sample standard deviation where n=24.

In regards to the specific effects of the experimental factors on the tensile strength of the pellets produced, moisture content, pressure, and grind size all had positive correlations towards an increase in tensile strength for RDF pellets. There does not appear to be any significant effect (P=0.1022) of die temperature on the pellet strength however. The sample in which the material was conditioned to 16% w.b. and had a grind size of 6.35 mm showed the greatest tensile strength across all pelleting conditions (temperature and pressure combinations).

For the biodegradable pellets, all factors had a significant individual effect on the tensile strength. Once again, the strongest pellets were formed by material that was 16% w.b. moisture content and of a larger grind size, 6.35 mm. reaching over 2 MPa. The biodegradable material pellets had a higher tensile strength than that of the RDF pellets, likely due to the fact that the fibers of the biodegradable material formed higher particle interlocking binding forces without the plastic fraction; the plastics also did not melt during pelleting, thus, they did not bind to the other particles in the material.

Untreated poplar and straw pellets produced by Shaw (2008) had mean tensile strengths between 0.5 and 1.3 MPa, while Tabil and Sokhansanj (1996) determined the tensile strength of alfalfa pellets to be between 0.2 and 2.2 MPa. Both the RDF and biodegradable material pellets showed very comparable tensile strengths with these values reported in literature for other biomass materials. Unlike these agricultural biomaterials however, increasing the moisture content of the MSW biomass helped to increase the tensile strength.

The Design Expert software determined the significant multiple factor interactions between pelleting parameters on tensile strength. Table 4.7 summarizes the analysis of variance (ANOVA) for all design interactions; values of "p-value" less than 0.05 indicate a significant interaction at a 95% confidence level. As with compact density, there is a three-factor interaction between moisture content, grind size, and pressure, although the analysis does not indicate the type of interaction.. Further, as temperature and grind size have only two treatment levels, only a linear interpretation of the data can be made.

Table 4.7: Significance of multiple factor interactions on tensile strength determined by analysis of variance (ANOVA) in Design Expert.

Interaction		p-Value	
Levels	Factors	RDF Material	Biodegradable Material
1FI [a]	Moisture Content	0.0036	<0.0001
	Temperature	0.1022	<0.0001
	Pressure	<0.0001	<0.0001
	Grind Size	<0.0001	<0.0001
2FI	Moisture Content x Temperature	0.0093	0.3111
	Moisture Content x Pressure	0.1363	0.0073
	Moisture Content x Grind Size	0.8520	<0.0001
	Temperature x Pressure	0.1287	0.1183
	Temperature x Grind Size	0.1264	0.0922
	Pressure x Grind Size	0.1092	0.0814
3FI	Moisture Content x Temperature x Pressure	0.2788	0.0427
	Moisture Content x Temperature x Grind Size	0.4604	0.0364
	Moisture Content x Pressure x Grind Size	0.0149	0.0004
	Temperature x Pressure x Grind Size	0.0863	0.1504
4FI	Moisture Content x Temperature x Pressure x Grind Size	0.2201	0.4039

[a] 1FI means one-factor interaction, indicates the number of factors in the statistical analysis

4.5.3.5 Factors Resulting in High Quality Pellets

Single pelleting trials are used to determine the factors that are significant in pelletization of biomaterials, as well as to determine the levels of each factor which produce higher quality pellets. These narrowed parameters were then tested further in pilot-scale pelleting to emulate industry-scale pelleting processes and to further evaluate the quality of pellets produced in a larger quantity.

The Design Expert software determined that moisture content and pressure are significant for both the RDF and the biodegradable materials. A grind size of 6.35 mm resulted in the highest compact density and tensile strength for both materials. As expected, a larger pressure, resulting from an applied load of 4 kN, resulted in higher compact pellet density in all cases. The effect of pelleting pressure on tensile strength is less apparent when moisture content and temperature are held constant. Further, the load applied in a full-scale pellet mill is dependent on the material, and is estimated to be higher than loads tested in the SPU trials; therefore, the pressure achieved in subsequent pellet trials will be uncontrolled.

A die temperature of 90°C results in the highest average compact density and tensile strength. Due to the desirability of reducing the energy required to produce pellets, pilot-scale pelleting will further evaluate the effect of temperature on the production of quality pellets by completing runs with and without preheating, corresponding approximately to the process values of 50°C and 90°C examined in the single pelleting trials.

In all of the diametral compression tests, pellets produced from material with 16% w.b. initial moisture content had the highest tensile strength. The effect of moisture content on compact density was less consistent; however, quality pellets were produced at all levels. Therefore, since high moisture contents are common in the raw MSW RDF-fluff material, a moisture content of 16% w.b. would be used for further trials.

4.5.4 Physical Characteristics of Pilot-Scale Produced Pellets

Physical characterization of the pellets produced using the CPM-CL5 pellet mill was completed following a storage period of one week. While the unit densities of samples appear to be very similar, the bulk densities of the biodegradable pellets (660 - 663 kg/m3) are slightly greater than that of the RDF samples (531 - 633 kg/m3). This may be a result of the poorer durability of the biodegradable pellets (88.2 - 91.7%), and therefore a greater number of fines to fill the pore spaces. The two RDF samples with the AK-2 added displayed the greatest durability (95.5 - 97.6%), although the AK-2 at such low quantities likely is not the attributing factor; however, it can be noted that the addition of AK-2 does not play an adverse role on the quality of the pellets produced. Commercially produced alfalfa pellets subjected to the durability test resulted in values of 96.1-98.6% (Larsen et al. 1996). Briquette durability for barley, canola, oat, and wheat straws were recorded as 42-95% by Song et al. (2010).

Table 4. summarizes the measured characteristics, including unit and bulk densities, durability, moisture content, and ash content for each sample.

While the unit densities of samples appear to be very similar, the bulk densities of the biodegradable pellets (660 - 663 kg/m^3) are slightly greater than that of the RDF samples (531 - 633 kg/m^3). This may be a result of the poorer durability of the biodegradable pellets (88.2 - 91.7%), and therefore a greater number of fines to fill the pore spaces. The two RDF samples with the AK-2 added displayed the greatest durability (95.5 -

97.6%), although the AK-2 at such low quantities likely is not the attributing factor; however, it can be noted that the addition of AK-2 does not play an adverse role on the quality of the pellets produced. Commercially produced alfalfa pellets subjected to the durability test resulted in values of 96.1-98.6% (Larsen et al. 1996). Briquette durability for barley, canola, oat, and wheat straws were recorded as 42-95% by Song et al. (2010).

Table 4.8: Physical properties and ash content of pilot-scale produced pellets from refuse-derived fuel (RDF) material and a biodegradable fraction.

Sample	Durability (kg/m^3)	Density		Moisture Content (% w.b.)	Ash Content (%)
		Unit (kg/m^3)	Bulk (kg/m^3)		
RDF: 16 % m.c No preheating 0% AK-2	93.2 (0.2) [a]	1187 (96) [b]	633 (7) [a]	11.6	39.4 (1.5) [c]
RDF: 16 % m.c No preheating 0.15% AK-2	95.5 (0.6)	1137 (59)	570 (12)	11.2	19.1 (1.3)
RDF: 16 % m.c Preheating at 50°C 0% AK-2	94.7 (0.5)	1122 (128)	531 (13)	6.7	28.2 (1.2)
RDF: 16 % m.c Preheating at 50°C 0.15% AK-2	97.6 (0.4)	1167 (73)	619 (5)	2.6	26.5 (1.1)
Biodegradables: 16 % m.c Preheating at 50°C 0% AK-2	91.7 (1.5)	1135 (60)	663(7)	3.5	19.7 (3.1)
Biodegradables: 16 % m.c Preheating at 50°C 0.15% AK-2	88.2 (1.4)	1164 (63)	660 (10)	3.2	22.9 (0.2)

[a] Value in parenthesis is standard deviation; n=3.
[b] Value in in parenthesis is standard deviation; n=20.
[c] Value in parenthesis is standard deviation; n=2.
[d] AK-2: Fuel additive used to increase fusion point of inorganic elements.

In terms of moisture content of the pellets, it can be noted that the samples that were not pre-heated by the conditioning chamber of the pellet mill prior to pelleting had a higher moisture content (11.2 - 11.6%) in pellet form than the samples that were preheated (2.6 - 6.7%). The additional travel time through the conditioning/preheating chamber of the pilot-scale pellet mill, would have dried the material prior to being pelleted; while in the single pelleting trials it was noted that a higher moisture content material at higher temperature pelleting was beneficial for both RDF and the biodegradable fraction materials, the ‘dried’ material during preheating produced comparable pellets to the unheated “moist’ samples. Preheating does appear to be a decent way to reduce the moisture content of the final product; as this is a challenge faced by the industry collaborator at the Edmonton Waste Management Centre.

Ash content of all pellets (19.1 - 39.4% d.b.) is greater than the 1% by mass required for first quality fuel pellet; this is likely due to the ‘dustiness’ of the material and consistent with past examination of RDF pellets. There appears to be a positive effect of adding AK-2 on reducing the ash content in the RDF pellets; further investigation would be necessary to evaluate the extent to which the ash content could be influenced.

A study in Greece found the local MSW stream to have an average ash content of 5.31% (Gidarakos et al. 2005), while a Nigerian study determined the ash content of its MSW to be 36-46 % (Daura et al. 2014). When compared to traditional biomass, woody materials typically have ash contents less than 1%, whereas herbaceous, fast-growing biomass such as straw and hay can contain 5-20% ash (Stahl et al. 2004). Therefore, since MSW is so variable, the ash content to can be very different depending on the source and composition. The “dusty” material used in this experiment however, is at the highest end of ash contents reported for biomass in literature, and remains a concern for conversion efficiency when discussed in terms of waste-to-energy. After sorting, an additional step of sieving fine particles could be implemented prior to particle size reduction; however, this may also increase the cost of operation.

4.5.5 Techno-Economic Analysis for Scaling-Up the Process Pelletizing MSW

The required throughput capacity of a full-scale pelletization operation for the EWMC, based on 140 000 Mg/yr contracted to Enerkem, would be 16.7 Mg/h assuming 350 days per year of continuous operation.

The study revealed that size reduction to 6.35 mm, as would be required for a 6.35 mm pellet die, was an unreasonable goal based on the desired throughput capacity and existing technologies. Many machines (>15) running in parallel would be required to achieve the minimum throughput and aggressive wear on the machine from the RDF would result in frequent and costly maintenance. A total cost estimate to achieve the desired throughput of 6.35 mm MSW RDF-fluff was $27.83/Mg.

Several manufacturers were able to provide information for the production of 6.35 mm diameter pellets, consistent with the initial pelleting trials; however, due to the unfeasibility of size reduction to facilitate this size of pellet, other options were also explored and reported. Two companies familiar with densification of RDF for other applications indicated that a densified product that is more uniform and easier to handle than the raw material could be produced from 25.4 mm or 50.8 mm material using a die with a diameter of 18-25 mm. Cost estimates for this process were provided as a feasible alternative, although further investigation into suitability of this densified product for the EWMC application would need to be evaluated. This iterative analysis is not within the scope of this research project, but is recommended for further study.

The average cost to produce 6.35 mm pellets from shredded material was \$10/Mg. When added to the cost for size reduction, the total cost to shred and densify the RDF material would be approximately \$38/Mg. In comparison, the average cost to produce crumb pellets (150 – 300 kg/m^3), soft pellets (250 – 400 kg/m^3), and hard pellets (>400 kg/m^3) were \$5.64/Mg, \$8.96/Mg, and \$16.20/Mg respectively. A complete summary of costs for each operation is found in Table 4.9.

Table 4.9: Summary of unit operations costs for size reduction and densification of refuse-derived fuel fluff from techno-economic feasibility study (Agnew and Harrison 2017).

Manufacturer (Model)	No. of Units	Throughput per unit (Mg/h)	Daily Run Time (h/day)	Capital Cost Total ($)	Capital Cost Cost/tonne ($/Mg)	Operating Cost Electricity ($/Mg)	Operating Cost Maintenance ($/Mg)	Operating Cost Labour ($/Mg)	Total Cost ($/Mg)
Size Reduction to 6.35 mm									
Vecoplan (Granulator)	15	2.2	12	5,000,000	1.59	unavailable	12.32	13.92	27.83
Pelletization (6.35 mm diameter pellets)									
CPM (7936-12)	4	5	20	2,619,000	0.83	3.00	2.67	3.09	9.59
Bliss Industries (B200B-175)	2	17	12	796,000	0.25	1.42	7.55	0.93	10.15
Pelletization using 50.8 mm fluff									
Kahl (Crumb)	2	15	13.3	1,455,000	0.46	2.00	2.00	1.03	5.49
	1	20	20	728,000	0.23	2.00	2.00	1.55	5.78
Kahl (Soft Pellets)	3	8	16.7	2,183,000	0.69	3.20	3.33	2.58	9.81
	2	14	14.3	1,455,000	0.46	3.20	3.33	1.11	8.10
Kahl (Hard Pellets)	5	4	20	3,636,000	1.15	6.40	6.67	3.09	17.32
	2	10	20	1,455,000	0.46	6.40	6.67	1.55	15.08
Lundell Enterprises	10	2.7	15	3,812,000	1.19	4.10	3.93	4.64	13.66

A techno-economic study by Shahrukh et al. (2016) reports that the cost of producing pellets from other biomaterials such as straw, forest residue, and switchgrass is $101/Mg, $96/Mg, and $97/Mg respectively. These values incorporate the full life-cycle costs of production, including transportation to the processing facility. Since MSW is a waste product, those costs not associated with size reduction and densification are recouped by the tipping fee charged by the city for disposing of the garbage and are therefore negligible. Thus, the cost to produce a quality densified MSW-RDF material is much lower than similar materials that have been investigated or biofuels application. Since the EWMC does not recoup any of the costs from sale of a converted product, they are likely interested in the least expensive option that successfully improves the consistency and handling of the RDF product that is supplied to Enerkem.

The market futures price of ethanol at end of day on May 18, 2017 was $0.526/L (Nasdaq 2017). The production capacity of the Enerkem facility is reported as 38 million L/year of ethanol from 140 000 Mg of feedstock (Enerkem 2017), resulting in a conversion estimate of 271 L/Mg. This translates to an approximate market value of $143/Mg of RDF. Therefore, depending on the cost associated with conversion to ethanol there may be potential for densification of RDF-fluff into a 6.35 mm product to be feasible.

4.6 Conclusions

The following conclusions can be drawn on the pelletization trials that were successfully conducted for the Edmonton Waste Management Centre:

1. The RDF-fluff supplied by the City of Edmonton consists of mostly paper, plastics, and textiles. The sample that was provided was very dry, 5.5% wet basis, and contained a large quantity of fines. The RDF-fluff was segregated into biodegradable (41% by mass) and plastic fractions (22% by mass) for pelletization trials to determine the potential for higher quality feedstocks.
2. From single pelleting trials, quality RDF and biodegradable material pellets were both formed at a grind size of 6.35 mm at 16% moisture under pelleting conditions of 90°C and 4000 N applied load.
3. From pilot-scale pelleting, it was determined that all of the samples produced durable pellets (88-94%), however, the ash content was around 20% for all samples which is expected for municipal solid waste, but does not meet requirements for high grade fuel pellets.
4. Pellets with 6.35 m diameter could be produced for an average cost of $38/Mg, although the aggressive process of the size reduction required indicates that it may not be a technically feasible option. Alternative densification operations were proposed as more feasible options, but they require further investigation to determine consistency with single pelleting trial parameter results and criteria.

Chapter 5

5 General Discussion

5.1 Introduction

This research project focused on the classification and densification of municipal solid waste in order to address two overlapping themes:

1. Is municipal solid waste (MSW) a good source for bioenergy development, in particular, as a feedstock for conversion to biofuels?
2. Is densification of MSW a feasible process to integrate into waste disposal systems in Canada?

This general discussion chapter aims to address these two themes with supporting evidence in the form of the technical results from the densification and characterization experiments conducted for this research project and the review analysis of MSW classification systems in Canada.

5.2 Municipal Solid Waste Suitability for Biofuels Development

Municipal solid waste has been gaining interest as a potential biomass feedstock for the production of advanced biofuels due to its organic nature and that it is a waste product not competing with land or food resources. A key theme of this research project was to evaluate various properties of MSW to determine its suitability for this purpose. Chapter 2 established the compositional elements of MSW that have energy recovery potential and indicated the types of conversion technologies available. It also alluded to the availability of MSW across Canada. Chapter 3 experimentally determined the bio- and thermochemical characteristics of MSW refuse-derived fuel, as well as the compression and relaxation properties of the biomass required for densification. Finally, Chapter 4 established the densification requirements for producing a quality RDF pellet product that could be use as a uniform biofuels feedstock for thermochemical conversion. This chapter also concluded with a techno-economic assessment of scaling up the pelleting process which provides information for comparing the cost of feedstock preparation to other biomass sources being investigated for biofuels.

The organic components in MSW that can be used for thermochemical conversion are plastics, paper, textiles, and food/yard wastes; the putrescible organics are more suitable to biochemical utilization however, by means such as composting or anaerobic digestion. The higher moisture content of the latter materials causes significant seasonal moisture content variability to an MSW stream and can reduce efficiencies of thermochemical conversion process. Very few inert materials are present in most MSW streams, typically consisting of less than 10% of the overall waste stream composition (Figure 2.2); however, any inorganic elements increase the inefficiencies of conversion as they contain no energy. Therefore, the three major difficulties with using MSW as a thermochemical conversion feedstock are the heterogeneous nature, high moisture content, and measurable inorganic fraction.

A very good reason for using MSW as a biofuels feedstock however, is the fact that it is a waste that municipalities wish to divert from landfill disposal. For example, the City of Edmonton, by collaborating with Enerkem to produce biofuels, has increased their landfill diversion rate to 90%. Therefore, the initial production cost is neutral when compared to purpose-grown energy crops; cost of transportation is already accounted for in a city’s waste management plan. Thus, information on the processing requirements required to produce a suitable biofuels feedstock is necessary to further evaluate the suitability for this utilization.

Thermochemical characterization determined that the higher heating value (HHV) of MSW-RDF is approximately 16 MJ/kg; the HHV for wheat straw is around 17.8 MJ/kg (Satpathy et al. 2014) and for wood it is around 20 MJ/kg (Krajnc 2015). The analysis also verified that MSW has a high ash content above 20% which is undesirable. The use of a fuel additive, AK-2, designed to reduce the fusion point of inorganic elements, showed potential for helping to reduce the ash content after combustion and may be worth investigating further.

Biochemical analysis was carried out to provide information as to whether there was potential for utilizing the biodegradable fraction of MSW as a feedstock for conversion to biofuels via ethanol fermentation. The result was that there is insufficient presence of reducing sugars in the material to pursue biochemical conversion for this biomass.

Densification is used to improve the density and handling of loose, low bulk-density biomass materials; pellets are a common form for biomass fuel products. Pelletization was investigated as a means to improve the quality of MSW-RDF as a biofuels feedstock; this would improve the uniformity of the very heterogeneous material, increase the energy density of the loose product, and allow the use of existing grain handling equipment. Quality of pellets is evaluated based on their compact density, dimensional stability, strength, and durability; material factors and process conditions both impact the optimal means for producing quality pellets. The single pelleting experiment conducted for this research project determined that quality pellets could be produced from RDF and the biodegradable fraction ground using a screen size of 6.35 mm, at a moisture content of 16% compressed by an applied load of 4 kN in a 90°C preheated die. Compact densities of 850-1000 kg/m^3 and 1100-1250 kg/m^3 were achieved for RDF and the biodegradable material respectively; this indicates that the energy density of the MSW biomass can be greatly improved by densification, as the original bulk density of the raw material was 55 kg/m^3. The pellets have adequate dimensional stability without the use of binders, and tensile strengths of up to 0.66 and 2.12 MPa for RDF and the biodegradable material, respectively; comparable values to other biomass such as poplar and wheat straw. Further, numerical modelling of the pelletization data indicates that the material is highly compressible (Walker model, Section 3.4.4) and is able to sustain unrelaxed stresses comparably to other biological materials (Peleg and Moreyra's model, Section 3.4.5). The pilot-scale pelleting experiment that was conducted concluded that a commercial pellet mill is capable of producing quality pellets on a larger scale. Durability of the produced pellets was above 90% (Table 4.8) which is very good. All of these experimental results indicate that a quality feedstock can indeed be produced from MSW-RDF.

Economic analysis indicates that the feasibility of scaling up the process of pelletizing MSW is comparable to that of other biomass such as straw and forest residues (Section 4.5.5). Further, there are already costs associated with disposing of the waste traditionally, so the pre-processing costs are negligible. Enerkem Alberta Biofuels has demonstrated that MSW-RDF is a viable feedstock in a fluff form, however, densification opens up improved opportunities for new projects. Unfortunately, the techno-economic feasibility of scaling up the production of 6.35 mm diameter pellets was determined to be challenging due to the intensive size reduction capabilities required to shred the RDF. Suggestions for other pellet sizes were supplied, but would require further investigation to determine the quality of those products compared to the pellets produced in the research project.

Overall, this research project determined that municipal solid waste is worth pursuing as feedstock from a techno-economical perspective due to the availability of biomass, the adequate energy content of the biomass, and the ability to produce a quality densified product to improve the handling and energy density of the material. Challenges remaining that must be addressed in order to improve the effectiveness of this feedstock are the high ash content of the material and equipment for enabling technically feasible scale-up of the pelletization process.

5.3 Integration of MSW Densification into Canadian Waste Disposal Systems

Canada has only recently been faced with the need to increase landfill diversion of municipal waste through new innovative technologies. Further, Canada is also searching for alternative fuels to those derived from fossil resources in order to address air pollution from the transportation industry and to combat climate change resulting from GHG emissions. It has been proposed that using MSW as a biofuels feedstock could help to bridge these two sustainability gaps, thus, the other theme of this research project was to evaluate whether MSW densification can be integrated into existing Canadian waste disposal and management systems to produce a quality biofuels feedstock. Chapter 2 reviewed the existing waste management programs for several jurisdictions in Canada and evaluated their suitability for pursuing biofuels development. Chapters 3 and 4 established the processing requirements for pelletizing MSW-RDF, providing both supporting and challenging evidence for how densification might be integrated into Canadian systems.

The Edmonton Waste Management Centre would be able to implement a densification process into their existing processing facility as they already produce RDF-fluff from their incoming MSW. This RDF-fluff preparation process includes separation of organics to their composting facility, removal of ferrous and non-ferrous metals, and size reduction to a 50.8 mm (2 in) material; pelleting equipment could be added to the end of this process. Other jurisdictions do not have this existing infrastructure; however, it could be established if waste-to-energy were an option that they were willing to pursue. The production of pellets could even be a diversion and recovery process implemented even if they are unable to set up their own waste-to-biofuels facility; a quality densified feedstock could be sent to other conversion facilities. A benefit of most of the jurisdictions under review when compared to Edmonton, is that they have a level of organics source separation which removes a large quantity of high moisture material from the waste stream. That said, residual food and yard waste, still accounting for up to 40% of the MSW stream in each case, can be used for thermochemical conversion since it is organic; however, some form of drying system would likely be required to remove some of the moisture. Regions that utilize processing and transfer facilities in their waste collection systems, Vancouver and Toronto, could adapt these locations to accommodate RDF pellet production before transfer of material to landfill.

Technical evidence from the pelleting experiments also helps to support densification or imply further investigation to enable the process effectively. Single pelleting trials indicated that temperature had some effect on the quality of pellets produced, however, the pilot-scale experiment concluded that the heat generated during the pelleting process was more than sufficient. Not requiring the addition of heat to the process decreases the energy requirement to produce the pellets; this energy reduction can reduce the overall costs, or justify the addition of other processes to improve quality. Moisture content was a recurring concern when discussing the use of MSW-RDF as a feedstock, as there is a threshold for moisture contents allowed for gasification, and the seasonal variability in moisture. Further, previous densification research projects have found that moisture contents around 10% w.b. are most suitable for producing quality pellets from biomass such as alfalfa, straw and, wood residues. Fortunately, this research project concluded that a higher moisture content, 16% w.b, was actually more suitable for producing quality RDF pellets (Section 4.5.3.5). This benefits the argument for integrating densification into Canadian waste management systems, as it means that less drying is required, if any, in the pre-processing of MSW; minimal drying translates to less energy required, reducing the cost of production. A drawback discovered in the thermochemical analysis of MSW-RDF is the high ash content attributed to dirty material with a high inert fines content (Table 3.1). One suggestion to reduce the amount of fines would be to implement a sieving process prior to size reduction; this added process could be justified due to the previous energy reductions based on unnecessary heating and drying costs. The techno-economic scale-up study report by PAMI (Table 4.9) provided information about existing equipment that is commercially available for implementing an MSW-RDF pellet production operation.

Ultimately, this research project determined that it would be possible to integrate MSW-RDF pellet production into existing Canadian waste disposal systems, supported by suggested processing conditions; however, there are some remaining challenges that require further investigation in order to improve the process. Most of all, the investment in new infrastructure is one of the larger barriers to implementation of this process in most regions other than Edmonton which already has an existing system; that said, this process can be seamlessly included in the pursuit of waste-to-energy alternatives for interested municipalities.

5.4 Closing the Knowledge Gap

The primary knowledge gaps prior to this research project were the state of a Canadian waste classification framework and the data regarding the characteristics of MSW and the parameters required to produce a quality, densified biofuels feedstock from MSW. Chapter 2 summarizes the review of existing MSW classification systems in Canada and an analysis of the suitability for pursuing biofuels production using MSW-RDF as a feedstock in select jurisdictions. This knowledge will assist in making decisions regarding the processing and utilization of MSW, particularly for biofuels development in jurisdictions across Canada Data analysis reported in Chapter 3 establishes a knowledge base regarding the thermochemical and biochemical characteristics of MSW-RDF as well as the compression and relaxation properties of the material. Results of experimental pelleting trials from bench-scale to pilot-scale, complete with a techno-economic feasibility study, establishes knowledge of the parameters required to produce quality pellets. All of this information allows informed decision making for going forward with the commercial production of a high quality biofuels feedstock from MSW biomass.

Chapter 6

6 Conclusions and Recommendations

The main objectives of this MSc project were: (i) to review the classification of MSW for biofuels applications; and (ii) to assess the pelleting and physico-chemical characteristics of MSW-RDF fluff.

To meet the first objective, the existing waste classification methods utilized in five Canadian jurisdictions were reviewed and each region was assessed for its potential to implement bioenergy technologies. A waste characterization study was also conducted for a sample of MSW RDF from the City of Edmonton.

A densification study was conducted to meet the second objective, including: determination of material pre-processing requirements, evaluation of compaction parameters by means of a single pelleting trial, a pilot-scale pelleting demonstration, bio- and thermochemical analysis of produced pellets, and a techno-economic scale-up feasibility study.

6.1 Conclusions

6.1.1 Review of Classification of Municipal Solid Waste for Biofuels Applications in Canada

a. Multiple Canadian jurisdictions were analyzed as to how municipal solid waste is classified and the suitability for waste-to-biofuels development in each region

    i. Each jurisdiction utilizes either a material-based or product-based classification framework for their municipal solid waste. Material-based classification frameworks are more appropriate for investigating alternative waste utilization opportunities for improving landfill diversion.

ii. Characterization studies were used either for monitoring of existing landfill diversion programs or for establishing new waste management strategies and assessing future projects.

iii. Each of the jurisdictions has the possibility of pursuing waste-to-biofuels development based on existing classification methodologies with minor adaptions, however, the greatest barrier is the lack of a driving incentive for producing biofuels to improve the city's environmental impact.

b. A classification framework for energy recovery created by Adapa et al. (2006) was discovered as a good system for classifying and assessing the suitability for biofuels development in Canadian regions.

c. The RDF-fluff supplied by the City of Edmonton consists of mostly paper, plastics, and textiles. The sample that was provided was very dry, 5.5% wet basis, and contained a large quantity of fines.

6.1.2 Assessment of the Pelleting and Physico-Chemical Characteristics of MSW-RDF Fluff

a. Municipal solid waste RDF-fluff and a segregated biodegradable fraction of the RDF-fluff were used as the material for pelletization trials to determine the potential for higher quality feedstocks. Each material was ground using a knife mill in order to ensure that all components, particularly the film plastics, were ground to the desired particle sizes of 3.18 and 6.35 mm for pelleting. The geometric mean diameter of the material ground using these screen sizes were approximately 0.6 mm and 1.1 mm respectively for both the RDF and biodegradable materials.

b. A single pelleting trial determined the material and process parameters required to produce quality pellets and evaluate the compression and relaxation properties of the RDF material.

i. Quality RDF and biodegradable material pellets were both formed at a grind size of 6.35 mm at 16% moisture under pelleting conditions of 90°C and 4000 N applied load.

ii. The compact density of RDF pellets was only affected by grind size, in which it was greatest with material that was ground with a 6.35 mm screen in the knife mill; compact density of biodegradable pellets increased with increasing pelleting load and temperature, while there was no significant effect of moisture content or grind size of the material.

iii. Both Walker's and Jones' model resulted in good fits to the experimental data and indicated that the biodegradable material had a higher compressibility than the RDF material for all conditions.

iv. Fitting of the Kawakita-Lüdde model to the compression data resulted in no significant correlation (P=0.05) between the model parameters and the experimental variables.

v. The Cooper-Eaton model indicates that the primary mechanism in the densification of RDF derived biomass is attributed to particle rearrangement, with some secondary influence from plastic deformation or particle fragmentation.

vi. Peleg and Moreyra's model, fit to the data, estimated the asymptotic modulus (E_a) for each sample and indicated that pellets formed from the RDF material had a higher E_a value than the biodegradable pellets; RDF-derived materials are determined to have comparable E_a values to literature values for other biological residues.

c. From pilot-scale pelleting, it was determined that all of the samples produced durable pellets (88-94%).

d. The thermochemical and biochemical characteristics of MSW-RDF were determined.

i. Ash content of all samples remains well above the 1% by mass required to be considered a first quality fuel pellet; this is likely due to the 'dustiness' of the material and consistent with past examination of RDF pellets.

ii. Proximate analysis verified that RDF has a high organic content, in which carbon accounts for approximately 40% of each of the pellet samples by mass.

iii. The higher heating value (HHV) was determined to be 14 – 16 MJ/kg for all samples using the Freidl et al. model and verified using experimental gross energy measurements for the two biodegradable material pellet samples.

iv. Very low glucose and non-existent xylose content of the biodegradable material samples conclude that biochemical conversion processes are not suitable for MSW RDF-fluff.

e. Pellets with 6.35 mm diameter could be produced for an average cost of $38/Mg, although the aggressive process of the size reduction required indicates that it may not be a technically feasible option. Alternative densification operations were proposed as more feasible options, but they require further investigation to determine consistency with single pelleting trial parameter results and criteria.

6.2 Recommendations for Future Research

6.2.1 Ash Content

In order to improve the energy efficiency of MSW as a biofuels feedstock, there is need to reduce the ash content, which is above 20%.

a. The addition of AK-2 appeared to reduce the ash content during combustion slightly for the pellet samples that were produced using 0.15% AK-2 by mass. Investigation into the extent to which AK-2 could be added to increase the ash content reduction while still producing durable pellets is recommended.

b. It would also be worthwhile to determine if a sieving process prior to initial size reduction would help to remove dirt and other inert fines from the MSW. Removing these materials, which account for up to 10% of the waste (Figure 2.2) should help to reduce the ash content as well.

6.2.2 Alternative Densified Fuel Products

The techno-economic study completed by PAMI indicated that while 6.35 mm pellets can be produced, the technical feasibility of shredding the MSW-RDF to a 6.35 mm product would be very hard on equipment and require many machines to meet a required throughput. The report suggested alternative pellet products that have been produced from MSW in other applications. Investigation into whether the parameters required to produce quality 6.35 mm pellets is consistent with the parameters required for these other products is recommended.

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Appendices

Appendix A: Supplementary Material for Chapter 3

Table A.1: Estimated parameters of the Walker's model for refuse derived fuel fluff and biodegradable material.

Grind Size (mm)	Moisture Content (% w.b.)	Applied Load (kN)	Die Temperature (°C)	Refuse Derived Fuel Fluff			Biodegradable Material		
				m	b	R^2	m	b	R^2
3.18	8	2	50	-0.3316	2.6488	0.966	-0.4207	2.8985	0.9413
			90	-0.3125	2.6381	0.9652	-0.4805	3.0707	0.9081
		3	50	-0.3283	2.6607	0.9581	-0.3169	2.5483	0.9717
			90	-0.305	2.7339	0.9519	-0.2859	2.3770	0.9274
		4	50	-0.3224	2.8923	0.9543	-0.3100	2.5707	0.9621
			90	-0.275	2.6603	0.9642	-0.3260	2.6039	0.9499
	12	2	50	-0.3614	2.8357	0.9459	-0.3211	2.4302	0.9641
			90	-0.3516	2.8352	0.9432	-0.3314	2.4547	0.9590
		3	50	-0.3602	2.9645	0.9324	-0.3618	2.6035	0.9460
			90	-0.3068	2.7042	0.9398	-0.3044	2.4179	0.9740
		4	50	-0.303	2.74	0.9483	-0.3288	2.6281	0.9414
			90	-0.3039	2.7495	0.9333	-0.3252	2.5896	0.9321
	16	2	50	-0.3371	2.7416	0.9641	-0.3277	2.2703	0.9493
			90	-0.2834	2.5018	0.9677	-0.2953	2.3022	0.9644
		3	50	-0.3283	2.813	0.9497	-0.2865	2.3791	0.9660
			90	-0.2639	2.5016	0.9606	-0.2547	2.2103	0.9659
		4	50	-0.3255	2.87	0.9436	-0.2832	2.4219	0.9639
			90	-0.2466	2.4031	0.9549	-0.2626	2.2881	0.9676
6.35	8	2	50	-0.3617	2.7029	0.9627	-0.3908	2.6955	0.9698
			90	-0.3279	2.5277	0.9587	-0.3713	2.5871	0.9702
		3	50	-0.3285	2.6395	0.9573	-0.3828	2.7333	0.9661
			90	-0.3025	2.3904	0.9583	-0.3523	2.2414	0.9547
		4	50	-0.3178	2.6574	0.9537	-0.3706	2.7350	0.9594
			90	-0.2879	2.5172	0.9605	-0.3510	2.6110	0.9542
	12	2	50	-0.3884	2.7607	0.9558	-0.3907	2.6649	0.9654
			90	-0.3535	2.4098	0.945	-0.3601	2.4996	0.9580
		3	50	-0.352	2.5551	0.9445	-0.3732	2.6965	0.9554
			90	-0.3233	2.607	0.9422	-0.3140	2.4063	0.9639
		4	50	-0.3239	2.6972	0.9429	-0.3140	2.5868	0.9639
			90	-0.2991	2.5942	0.9481	-0.3378	2.5894	0.9536
	16	2	50	-0.3654	2.5917	0.9313	-0.3983	2.6603	0.9640
			90	-0.3281	2.386	0.9311	-0.3866	2.5400	0.9585
		3	50	-0.3197	2.5247	0.9334	-0.3565	2.5817	0.9529
			90	-0.3135	2.4656	0.9237	-0.3419	2.5009	0.9550
		4	50	-0.3017	2.531	0.9279	-0.3472	2.6257	0.9515
			90	-0.2672	2.2521	0.8505	-0.3142	2.4531	0.9526

Table A.2: Estimated parameters of the Jones' model for refuse derived fuel fluff and biodegradable material.

Grind Size (mm)	Moisture Content (% w.b.)	Applied Load (kN)	Die Temperature (°C)	Refuse Derived Fuel Fluff			Biodegradable Material		
				m'	b'	R^2	m'	b'	R^2
3.18	8	2	50	0.1685	7.3392	0.9932	0.2049	7.6121	0.9827
			90	0.1544	7.2496	0.9920	0.2044	7.6071	0.9832
		3	50	0.1581	7.1850	0.9901	0.1869	7.5497	0.9911
			90	0.1498	7.1732	0.9854	0.1675	7.5273	0.9963
		4	50	0.1577	7.1550	0.9874	0.1686	7.4768	0.9950
			90	0.1389	7.1215	0.9906	0.1735	7.5193	0.9920
	12	2	50	0.1776	7.2941	0.9824	0.1820	7.6064	0.9936
			90	0.1669	7.2343	0.9816	0.1861	7.6327	0.9921
		3	50	0.1691	7.2046	0.9778	0.1826	7.5516	0.9878
			90	0.1522	7.1825	0.9792	0.1758	6.9986	0.9918
		4	50	0.1529	7.1657	0.9844	0.1797	7.5224	0.9868
			90	0.1491	7.1513	0.9772	0.1800	7.5429	0.9827
	16	2	50	0.1630	7.2590	0.9919	0.1822	7.5875	0.9871
			90	0.1467	7.2330	0.9916	0.1738	7.5938	0.9926
		3	50	0.1574	7.1953	0.9855	0.1672	7.5094	0.9940
			90	0.1379	7.1717	0.9881	0.1588	7.5206	0.9930
		4	50	0.1547	7.1593	0.9836	0.1653	7.5104	0.9937
			90	0.1359	7.1040	0.9857	0.1617	7.5135	0.9945
6.35	8	2	50	0.1869	7.3736	0.9952	0.2095	7.6336	0.9973
			90	0.1710	7.3567	0.9916	0.2070	7.6558	0.9974
		3	50	0.1742	7.3156	0.9917	0.2093	7.6070	0.9969
			90	0.1612	7.2935	0.9914	0.2018	7.6443	0.9922
		4	50	0.1685	7.2721	0.9897	0.2079	7.6052	0.9960
			90	0.1511	6.6507	0.9922	0.2043	7.6311	0.9944
	12	2	50	0.1946	7.4336	0.9903	0.2126	7.6791	0.9687
			90	0.1814	7.3940	0.9857	0.2089	7.1264	0.9925
		3	50	0.1814	7.3940	0.9857	0.2065	7.6205	0.9936
			90	0.1681	7.3102	0.9849	0.1892	7.6106	0.9947
		4	50	0.1708	7.2743	0.9851	0.1934	7.5744	0.9931
			90	0.1575	7.2357	0.9868	0.1957	7.5831	0.9924
	16	2	50	0.1970	7.4418	0.9804	0.2254	7.7398	0.9940
			90	0.1868	7.4619	0.9797	0.2092	7.7234	0.9942
		3	50	0.1779	7.3261	0.9795	0.1997	7.6281	0.9918
			90	0.1777	7.3543	0.9747	0.1980	7.6426	0.9921
		4	50	0.1685	7.2579	0.9759	0.1942	7.5711	0.9922
			90	0.1517	6.6668	0.8948	0.1883	7.5827	0.9902

Table A.3: Estimated parameters of the Kawakita and Ludde's model for refuse derived fuel fluff and biodegradable material.

Grind Size (mm)	Moisture Content (% w.b.)	Applied Load (kN)	Die Temperature (°C)	Refuse Derived Fuel Fluff			Biodegradable Material		
				a_1	b_1	MSE	a_1	b_1	MSE
3.18	8	2	50	0.7517	605.3	0.0002	0.9035	356.3	0.0002
			90	0.7219	561.4	0.0002	0.9042	634.7	0.0005
		3	50	0.7533	453.0	0.0003	0.7699	509.2	0.0002
			90	0.8477	658.7	0.0004	0.7172	383.2	1.1691
		4	50	0.8133	516.5	0.0004	0.8353	414.5	0.0001
			90	0.6135	275.1	0.0000	0.8964	440.2	0.0002
	12	2	50	0.9001	248.1	0.0003	0.8838	467.2	0.0003
			90	0.8868	285.4	0.0004	0.8312	474.9	0.0002
		3	50	0.8717	297.4	0.0003	0.8943	386.2	0.0004
			90	0.8627	369.5	0.0003	0.7944	405.3	0.0003
		4	50	0.8558	391.7	0.0002	0.8554	467.3	0.0003
			90	0.8545	412.9	0.0003	0.9078	372.8	0.0002
	16	2	50	0.6478	339.9	0.0000	0.8360	427.4	0.0002
			90	0.6087	331.4	0.0000	0.7188	343.9	0.0001
		3	50	0.6566	341.6	0.0000	0.6692	307.6	0.0000
			90	0.6081	332.1	0.0000	0.6542	327.8	0.0000
		4	50	0.6759	351.5	0.0001	0.6776	297.0	0.0000
			90	0.6179	330.6	0.0000	0.6669	284.8	0.0000
6.35	8	2	50	0.8908	470.8	0.0006	0.7284	303.5	0.0000
			90	0.8912	669.0	0.0004	0.7242	288.7	0.0000
		3	50	0.8902	461.5	0.0004	0.7566	288.6	0.0001
			90	0.8898	377.7	0.0003	0.7525	315.9	0.0001
		4	50	0.8882	424.4	0.0013	0.7800	297.6	0.0006
			90	0.8593	488.4	0.0006	0.7594	293.8	0.0001
	12	2	50	0.9162	326.6	0.0015	0.7347	309.6	0.0000
			90	0.9312	240.1	0.0007	0.7484	322.2	0.0001
		3	50	0.9048	261.4	0.0005	0.7623	329.5	0.0001
			90	0.8936	435.9	0.0005	0.7081	295.0	0.0000
		4	50	0.8990	227.4	0.0004	0.7336	308.9	0.0000
			90	0.8797	514.0	0.0004	0.7775	368.4	0.0007
	16	2	50	0.9104	364.1	0.0003	0.7775	368.4	0.0001
			90	0.9344	218.9	0.0004	0.9220	383.2	0.0002
		3	50	0.9039	250.3	0.0003	0.8179	665.2	0.0001
			90	0.9089	273.0	0.0003	0.8112	425.6	0.0001
		4	50	0.8960	245.4	0.0003	0.8415	616.9	0.0003
			90	0.9002	227.3	0.0004	0.7721	434.2	0.0001

Table A.4: Estimated parameters of the Cooper-Eaton model coefficients for refuse derived fuel fluff.

Grind Size (mm)	Moisture Content (% w.b.)	Applied Load (kN)	Die Temperature (°C)	Model Parameters				
				a_2	a_3	k_2	k_3	R^2
3.18	8	2	50	0.779	0.201	0.399	8.105	0.999
			90	0.761	0.137	0.453	8.528	0.999
		3	50	0.776	0.132	0.363	9.643	0.999
			90	0.877	0.074	0.087	6.439	0.995
		4	50	0.826	0.105	0.276	9.780	0.997
			90	0.665	0.189	0.805	13.267	1.000
	12	2	50	0.846	0.091	0.124	7.037	0.998
			90	0.886	0.064	0.129	8.312	0.995
		3	50	0.901	0.059	0.182	19.613	0.967
			90	0.880	0.072	0.114	7.430	0.998
		4	50	0.859	0.093	0.123	7.457	0.996
			90	0.866	0.084	0.105	6.356	0.998
	16	2	50	0.696	0.169	0.638	9.044	1.000
			90	0.663	0.171	0.668	9.285	1.000
		3	50	0.728	0.148	0.672	11.976	1.000
			90	0.690	0.166	0.682	9.066	0.999
		4	50	0.719	0.163	0.585	9.997	1.000
			90	0.680	0.177	0.679	10.427	1.000
6.35	8	2	50	0.849	0.122	0.128	3.690	0.980
			90	0.867	0.102	0.058	3.874	0.998
		3	50	0.841	0.123	0.058	3.169	0.998
			90	0.844	0.122	0.046	2.885	0.996
		4	50	0.831	0.138	0.056	3.605	0.998
			90	0.854	0.115	0.133	5.476	0.998
	12	2	50	0.848	0.126	0.067	3.547	0.998
			90	0.874	0.093	0.074	2.633	0.994
		3	50	0.870	0.119	0.104	8.739	0.969
			90	0.878	0.093	0.069	4.114	0.995
		4	50	0.880	0.094	0.099	5.737	0.999
			90	0.847	0.118	0.051	3.386	0.993
	16	2	50	0.908	0.076	0.113	5.815	0.998
			90	0.913	0.076	0.085	4.049	0.999
		3	50	0.899	0.080	0.109	5.569	0.998
			90	0.897	0.088	0.093	4.132	0.998
		4	50	0.864	0.115	0.137	4.329	0.997
			90	0.884	0.097	0.073	4.368	0.997

Table A.5: Estimated parameters of the Cooper-Eaton model for biodegradable material.

Grind Size (mm)	Moisture Content (% w.b.)	Applied Load (kN)	Die Temperature (°C)	Model Parameters				
				a_2	a_3	k_2	k_3	R^2
3.18	8	2	50	0.877	0.091	0.073	5.313	0.998
			90	0.886	0.068	0.050	3.366	0.999
		3	50	0.777	0.180	0.449	8.480	0.996
			90	0.775	0.193	0.619	12.406	0.999
		4	50	0.837	0.130	0.231	8.400	0.998
			90	0.899	0.084	0.075	6.226	0.998
	12	2	50	0.885	0.092	0.127	6.158	0.998
			90	0.858	0.122	0.267	7.528	0.998
		3	50	0.894	0.086	0.095	6.608	0.921
			90	0.829	0.172	0.403	10.267	0.865
		4	50	0.871	0.111	0.210	8.608	0.998
			90	0.917	0.072	0.087	8.293	0.998
	16	2	50	0.908	0.061	0.280	11.641	0.924
			90	0.810	0.153	0.543	8.534	0.964
		3	50	0.746	0.193	0.699	10.235	0.998
			90	0.761	0.211	0.680	10.266	1.000
		4	50	0.747	0.208	0.728	11.821	0.999
			90	0.756	0.226	0.768	13.291	1.000
6.35	8	2	50	0.769	0.204	0.717	10.652	1.000
			90	0.769	0.212	0.700	9.748	0.999
		3	50	0.781	0.211	0.734	12.060	1.000
			90	0.834	0.168	0.681	14.649	0.989
		4	50	0.806	0.185	0.609	10.004	0.990
			90	0.807	0.210	0.644	12.677	0.999
	12	2	50	0.797	0.189	0.723	11.234	1.000
			90	0.813	0.133	0.637	8.522	0.995
		3	50	0.805	0.185	0.601	11.328	0.999
			90	0.792	0.212	0.768	10.962	1.000
		4	50	0.786	0.213	0.696	10.773	0.999
			90	0.813	0.186	0.569	10.203	0.999
	16	2	50	0.849	0.149	0.073	3.905	0.972
			90	0.833	0.162	0.044	2.496	0.998
		3	50	0.818	0.174	0.098	4.242	0.998
			90	0.804	0.189	0.427	3.597	0.999
		4	50	0.828	0.169	0.292	5.297	0.999
			90	0.969	0.033	0.682	4.822	0.976

Table A.6: Estimated parameters of the Peleg and Moreyra's model, asymptotic modulus (E_A) and percent average relaxation (PAR) for an applied loading force of 4 kN.

Grind Size (mm)	Moisture Content (% w.b.)	Die Temperature (°C)	Model Coefficients				
			k_3	k_4	R^2	E_a	PAR
Refuse Derived Fuel Fluff Material							
3.18	8	50	5.4363	3.2712	0.9997	102.3083	31.4112
		90	5.4331	3.5054	0.9997	105.9099	28.0047
	12	50	5.6062	2.7574	0.9995	94.3292	35.4583
		90	5.8815	3.0690	0.9996	99.7625	31.8987
	16	50	9.8367	3.1255	0.9986	100.2806	31.8577
		90	15.7950	4.5133	0.9985	117.9925	21.6536
6.35	8	50	4.3648	3.1264	0.9998	102.9190	31.5250
		90	6.0228	3.5791	0.9997	108.6824	27.4371
	12	50	6.8450	3.0477	0.9993	100.2432	32.2302
		90	6.9565	3.3166	0.9995	104.0980	29.4298
	16	50	9.3718	3.1884	0.9988	102.2640	31.1712
		90	16.4102	4.2884	0.9980	116.6487	22.6235
Biodegradable Material							
3.18	8	50	3.8550	2.9439	0.9999	96.2346	33.4692
		90	4.1158	2.8521	0.9997	99.2291	34.5839
	12	50	4.8178	3.0749	0.9997	98.0572	32.0218
		90	5.2031	3.3858	0.9997	102.0733	29.1071
	16	50	6.9261	2.6648	0.9991	91.0696	36.5165
		90	6.2939	2.9217	0.9995	95.5640	33.3961
6.35	8	50	4.6555	3.0487	0.9997	96.8830	32.2938
		90	4.1322	3.3897	0.9998	102.4345	29.1608
	12	50	5.1640	2.8286	0.9996	93.8167	34.7149
		90	5.7374	3.2508	0.9996	99.8821	30.2478
	16	50	7.3068	2.5823	0.9987	89.1139	37.6792
		90	7.3789	3.1048	0.9993	98.4479	31.5154

Appendix B: Supplementary Material for Chapter 4

Table B.1: Particle Size distribution of municipal solid waste refuse-derived fuel fluff according to ASTM E828.

Sieve Size	% Retained
> 5.08 cm	0.0 (0)*
1.91 cm – 5.08 cm	41.4 (5.8)
1.27 cm – 1.91 cm	19.2 (4.1)
6.35 mm – 1.27 cm	24.4 (2.3)
4.76 mm – 6.35 mm	4.9 (1.6)
1.41 mm – 4.76 mm	4.1 (1.2)
< 1.41 mm	6.1 (1.4)

*Value in parentheses is standard deviation, n=4.

Table B.22: Percent by mass amount of material in each size range following particle size analysis.

	RDF		Biodegradable Material	
	3.18 mm	6.15 mm	3.18 mm	6.15 mm
> 4.76 mm	1.33	4.92	0.14	20.80
3.36 - 4.76 mm	1.00	8.79	0.01	13.55
2.38 - 3.36 mm	3.03	16.40	1.40	13.85
1.68 - 2.38 mm	17.62	16.50	15.71	11.53
1.19 - 1.68 mm	23.86	11.56	20.70	7.77
841 µm - 1.19 mm	12.35	6.49	12.64	4.25
595 - 841 µm	8.51	6.86	9.61	4.13
420 - 595 µm	7.05	6.34	7.76	3.19
297 - 420 µm	6.31	6.52	6.25	4.75
210 - 297 µm	6.24	6.19	5.84	3.33
149 - 210 µm	5.60	5.26	6.61	3.44
105 - 149 µm	1.80	3.10	3.27	2.29
< 105 µm	5.31	1.07	10.06	7.12
d_{gw}	0.666	0.952	0.503	1.193
S_{gw}	0.794	1.250	0.705	2.249